University of Alberta

The Cadotte Member of the Boulder Creek Formation, Commotion Creek and Dokie Ridge, Northeast British Columbia

by

Jeffrey Paul Reinprecht ©

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"Bought the Ticket, Take the Ride"

- Hunter S. Thompson,

Fear and Loathing in Las Vegas

This thesis is dedicated to my parents
Paul and Jacquie Reinprecht
for all the love and support they've given me
throughout my long years in University
Thank You

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CHAPTER 1 - INTRODUCTION

Stratigraphic nomenclature of the conglomeratic interval contained within the Lower Cretaceous Boulder Creek Formation has undergone an evolution. The Cadotte conglomerate facies have been referred to as the Commotion Formation, the Boulder Creek Formation, the Peace River Formation, the Cadotte Member of the Boulder Creek and Peace River Formations. For simplicity, the Cadotte Member will be referred to as the Cadotte herein.

The Lower Cretaceous (lower to middle Albian) of the Western Canadian Sedimentary Basin consists of sedimentary deposits that define a large eastward-tapering clastic wedge (Figure 1.1). Abundant coarse-grained sedimentary deposits characterize this sedimentary wedge. These deposits are represented by the multicylic Gates Formation, as well as the Cadotte and Walton Creek Members of the Boulder Creek Formation (Stott, 1982). Both the Gates and Boulder Creek Formations are part of the larger Fort St. John Group (Table 1.1). The Gates Formation and the Cadotte Member are dominated by regressive coastal deposits that prograded north to varying extents into the Moosebar and Hulcross seas (Caldwell, 1983). A thick shale unit separates the upper Gates from the overlying Cadotte. This shale, known as the Hulcross Formation, represents a major flooding of coastal, coastal plain and alluvial deposits following emplacement of the upper Gates, and prior to deposition of the Cadotte-age shoreline regressions. The landward extent of this flooding controlled the location of Cadotte shoreline initiation. A conformable transition from one stratal unit to the other is placed at the first sandstone bed sitting stratigraphically above a continuous section of siltstones and shales (Stott, 1982). Together, the Hulcross and Cadotte make up the third order (1-3 m.y.) Hulcross Transgressive-Regressive couplet of Caldwell (1983)(Figure 1.1) contained within the second order (6-10 m.y.) Kiowa-Skull Creek Marine Cycle (Kauffman and Caldwell, 1993).

The Walton Creek Member overlies the Cadotte and is considered to be part of the second order Kiowa-Skull Creek Marine Cycle (Caldwell, 1983). It contains extensive evidence of flooded alluvial valleys, which led to the development of large estuarine (and associated) environments, common to coastlines undergoing transgression (Leckie, 1991B; Leckie 1991C; Leckie and Singh, 1991). This Walton Creek shoreline transgression terminates at a time of maximum flooding, during the linking of the Boreal (Shaftesbury) and more equatorial Gulfian Seas. This joining of the Boreal and Gulfian seas is manifested in the rock record by the thick accumulation of Hasler Formation marine shales (Figure 1.1).

1.1 Description and Objectives of the Study

The objective of this study was to describe and interpret the Cadotte Member of the Boulder Creek Formation from two outcrop localities, one at Commotion Creek (Commotion Formation type section) and the other at Dokie Ridge (Commotion Formation reference section). The bulk of the study focused on Commotion Creek due to the ease of accessibility and quality of the outcrop. Both study areas are located in northeast British Columbia (Figure 1.2) and each contains a moderate to thick section of coarse-grained sedimentary rocks. Following outcrop description, the units were used to constrain the genetic depositional system responsible for the emplacement, distribution and modification of the original coarse-grained, reservoir quality facies. As well, inferences and discussion regarding the position of local basin characteristics in a more regional setting (through literature comparisons) were addressed. This includes discussions pertaining to sedimentary processes ranging in scale from seasonal (bi-yearly), to as much as 10 million years (Exxon third order sea level changes). In essence, the goal of the study was to geologically analyze and document all relevant sedimentary and stratigraphic characteristics of the outcrop, and where possible, relate this study to exploration and exploitation of stratigraphically equivalent coarse-grained, hydrocarbon reservoirs of the Cadotte.

1.2 Study Area

The field portion of this project was carried out at two different outcrops within the Canadian Rocky Mountain Fold and Thrust Belt (Figure 1.3). These outcrops are named in accordance with the primary geomorphic features where they are located, notably Commotion Creek and Dokie Ridge (Figure 1.4). Both areas are west of the town of Chetwynd, in northeast British Columbia (Figure 1.3).

Commotion Creek lies on the western edge of N.T.S.[1] map sheet 93 P/12, approximately 20 km west of the town of Chetwynd along the John Hart-Peace River Highway. It can be accessed by conventional vehicle and consists of three principle outcrops: Commotion West, Commotion East and Commotion Creek (Figure 1.5). Two of these principle areas (Commotion Creek and Commotion East) can be accessed by a short 0.1-3.5 kilometer drive north along the Walton Creek Forest Service road. Commotion East (oriented east/west) is located 100 m north of the highway and outcrops along the north and east side of the road. Not much emphasis has been placed on this area as extensive lichen and ground cover, as well as vertically discontinuous outcrops, inhibit the availability of reliable data. The Commotion Creek outcrops (oriented approximately north/northwest to south/southeast) are located below the elevation of the western edge of the Walton Creek Forest service road. These outcrops are located in a narrow creek valley approximately 30-40 meters deep trending parallel to the road.

Commotion West (oriented approximately east/west) is accessible from a gravel secondary road located approximately 1 km west of the Walton Creek Forest service road turnoff. A small public and slightly forested dirt road runs east/west paralleling the outcrop some 50 to 100 meters south of the outcrop face. This road is commonly used by recreational climbers to gain access to the high vertical cliffs of Commotion West (which provide them with challenging climbing routes). As well, after obtaining permission from a local landowner, a small private road can be used to access the top of Commotion West.

---

[1] N.T.S. - National Topographic System.

The Commotion area outcrops are contained within a broad shallow north/south trending anticline. Commotion Creek runs parallel to the axial plane of this fold (due to more extensive structural jointing and fracturing), while Commotion West and Commotion East lie on the shallow dipping west and east limbs (Figure 1.5).

Commotion West and Commotion East is a depositional shoreline-apparent strike parallel section while Commotion Creek is an apparent dip-oriented exposure (Figure 1.6). The Commotion Creek (CC) dip section continuously trends relatively north/south for up to 425 meters in 5.0 to 25 meter high vertical cliff faces which have been cut by Commotion Creek. The outcrop is terminated at its southern extent by ground cover and at its northern extent by a 20 - 25 meter high waterfall, north of which the outcrop is buried by ground cover. The Cadotte member outcrops along both sides of the creek. These outcroppings merge to the north at the waterfall, and diverge to the south. Many of the often heavily fractured cliff faces are also extensively covered by either moss, lichen or a white to tan carbonate crust.

The depositional strike oriented outcrops run east and west from the southern extent of the creek valley. They have been named Commotion East (CE) and Commotion West (CW), respectively. Commotion East consists of a series of vertically discontinuous outcrops (exposed as benches) separated by ground cover, running east-west. The western extent of CE does not merge at the surface with outcroppings at the southern end of the creek valley. The Commotion East exposures take one of three principle forms. The basal portion of the outcrop is exposed in a road cut, which is buried beneath surface cover at its eastern extent, and beneath a gravel road/surface cover at its western extent. The outcrop is approximately 100 meters long, and 10 meters high[2] at its eastern extent tapering westward to less than 1 meter. The middle portion of the Commotion East outcrops is located in a sandstone quarry that is intensely fractured due to blasting associated with quarry excavation. It is approximately 75 meters long and ranges from approximately 1 to 10 metres high. The upper outcrop consists of a series of vertically discontinuous benches at its western extent, these benches range from 1 to 3 meters in height per bench, for a minimum of 1, and maximum of 3, benches. Further east only a single bench is present ranging between 6 to 8 meters high. This section is continuously exposed along strike for approximately 500 meters. The outcrop is truncated by ground cover at its western margin and surface erosion associated with an emerging thrust fault at its eastern end.

---

[2] Vertical measurements uncorrected for structural dip.

Commotion West is exposed as a 5 to 25 meter high vertical cliff face running perpendicular to the southern extent of Commotion Creek. The faces are vertically continuous and often encrusted with a brown to tan carbonate crust. The section is approximately 550 meters long in an east-west orientation, and can contain locally abundant fracture surfaces. Overlying the section is a bench of conglomerates, sandstones and shale that range in height from 3 meters to not exposed. The bench is recessed approximately 5 to 10 meters north from the upper cliff face edge, and is discontinuous in an east-west orientation leading to a pinch and swell appearance. This location is named Commotion West Top.

For reference, the Commotion Creek study area is located approximately 100 km northwest of the Noel gas field of northeast British Columbia and approximately 140 km northwest of the Elmworth gas field of northwest Alberta (Figure 1.7).

Stott (1961B) noted a good Boulder Creek reference section at Dokie ridge in northeast British Columbia. The Dokie Ridge locality is accessible along a B.C. Hydro power-line service road using 4-wheel drive vehicles (equipped with a winch). The turnoff for this road is located approximately 40-50 km west of the town of Chetwynd where the John Hart-Peace River Highway crosses Crassier Creek. Following the turnoff, the base of Dokie Ridge can be reached by following the Hydro road north and east. The B.C. Hydro power line service road is rugged and may not be fit for travel during and following periods of high rainfall, as forestry clear cutting has allowed the numerous creeks to swell rapidly (due to quick runoff in the catchment area) and washout the infrequently traveled dirt roads. From the base of the main ridge (evident as a resistant southward dipping conglomerate outcrop) the top of the main ridge can be accessed by a steep half to one hour hike. Alternatively, the ridge may be accessed by helicopter, which is much less difficult and less time consuming. However, helicopter access may be impeded by high westerly derived winds that gust in a large east/west trending valley at the eastern head of which Dokie Ridge sits. Dokie Ridge is at approximately 1,371.5 m (4,500 ft) elevation and as such is prone to rapid fluctuations in weather conditions.

The Cadotte member at the Dokie Ridge locality outcrops along the east limb of an anticline trending approximately 316 degrees. Due to the resistant nature of the outcrop, Cadotte sediment forms a prominent ridge separating the more recessive underlying Hulcross siltstones and overlying Paddy sandstones (Figure 1.4). This ridge is crosscut by two westward draining creek valleys. Chert rich conglomeratic portions of the upper Cadotte are extensively covered by black lichen making description and study extremely difficult, however lichen colonization of the dominantly quartz rich lower Cadotte sandstones is minimal and the flaggy weathering profile, common to these sandstones, is extremely helpful in its recognition and description.

1.3 Methodology

Nineteen outcrop sections were logged at the Commotion Creek location, while two were described at Dokie Ridge. Outcrop sections at Commotion Creek are dominantly vertical to overhanging, and were logged safely by means of rappelling. A tape measure was anchored to the base of a tree on the top of the cliff face and depths were corrected and shifted to a zero value upon completion of the section log. The Dokie Ridge sections were measured using a Jacobs Staff and Brunton compass to ensure accuracy and consistency of the staff dip angle and direction. Numerous photos were taken using a Cannon Eos II camera with both macro- and wide-angle lenses. Multiple outcrop panoramas were constructed from photographs taken from both a helicopter and the ground. These photo mosaics were then used to help delineate facies boundaries and spot subtle preserved depositional surfaces and bed forms. Samples were taken at apparent lithology transitions or at regular intervals. These samples provided an aid in drafting sections and allowed for minor petrographic analysis (to augment facies descriptions). Outcrops were also logged with a Scinollometer for gamma radiation emissions. These readings were used to construct geophysical logs (Gamma Ray) for their associated geologic sections, however, due to the relatively consistent nature of the sediment these sections show no significant variation.

Gibson (1992) reported that 33 cored Boulder Creek coal exploration boreholes exist between the Grand Cache and Chetwynd areas. However, attempts to log coal exploration borehole cores from the Commotion Creek study area revealed that most of the rock had been used in the construction of the foundation of the core storage facility expansion at Charlie Lake, near Ft. St. John, northeast British Columbia. The only coal exploration borehole core that could be located is Gulf Trefi 80-01, shown on Figure 1.2. It was logged and incorporated into the stratigraphic framework established at outcrop scale. As well, two conventional drill cores (also shown on Figure 1.2) from the Stone Creek petroleum field (not a productive Cadotte field) were logged and incorporated into the study. All drill cores were examined at the core research facility in Charlie Lake, near Ft. St. John, northeast British Columbia. Core data was then entered into Applecore and those used in the final thesis (as well as the remainder of the figures) were digitized using Adobe Photoshop and Illustrator.

A shallow drill core program was carried out at Commotion Creek to provide information that would complement the outcrop descriptions. The hole was drilled and cored using a continuous wire line system, and recovered core from no greater than 40 meters depth (Figure 1.9). This core provided a pristine example of the sedimentary facies present in the Commotion Creek study area and was desirable due to the presence of intense carbonate and lichen commonly encrusting the faces of the outcrops. As well, this core provided a sample of preserved Cadotte sedimentary rock of the same scale with which a petroleum geologist would be expected to work while defining a play or delineating a reservoir. In essence, this core provides a geologist with the means to evaluate his/her own exploration models of the Cadotte and compare what a 3 inch thick piece of rock looks like on a scale more comparable to the actual depositional setting.

Processing of samples for the purpose of Biostratigraphic analysis was carried out at the University of Alberta. Samples were first broken down using a Jaw Crusher, and then placed in a beaker containing 30% hydrogen peroxide. The hydrogen peroxide oxidized most of the organic material in the hopes that it would help free any siliceous microfauna. These samples were then sieved using standard 10, 16, 18, 80 and 200 mesh screens. Following the sieving, a standard binocular microscope was used to analyze the rock material. Despite repeated attempts and analysis of 5 samples, no microfauna was recovered.

1.4 Economic History and Significance

Early oil and gas exploration revealed that the coarse-grained, well-sorted nature of marine units in the Cadotte sandstone were favorable for the preservation of economic porosity and permeability. Coupled with their encasement in fine-grained impermeable shales, which provided a seal, these units made for good potential hydrocarbon reservoirs (Stott, 1962). As petroleum companies actively explored these deposits for reserves, gas pools were found at Sunrise, Dawson Creek and Pouce Coupe (Stott, 1962)(Figure 1.7). Despite success in these regions, petroleum exploration for Cadotte member reservoirs wasn't considered high priority until 1976, when Canadian Hunter took a gamble on a region they termed the "Deep Basin" (Figure 1.9), and spudded a well in an area of northwest Alberta known as Elmworth (Figure 1.7). Canadian Hunter's well came in, and they were immediately launched into the petroleum industry spotlight. The Elmworth field was classified as a super giant, containing up to "17 trillion cubic feet of proved plus probable gas and 1 billion barrels of natural gas liquids" trapped in numerous lower Cretaceous formations (Masters, 1984B). This discovery was so significant that in 1984 Canadian Hunter, in conjunction with the American Association of Petroleum Geologists, published a memoir devoted solely to the geology and reservoir characteristics of the Elmworth Field of Western Canada's Deep Basin (Masters, 1984A). This publication, as well as related research, revealed that the Deep Basin represents a significant accumulation of gas trapped down structural dip from extensive regional water trends (McMaster, 1981). This gas trap is characterized by continual gas generation (from numerous lower Cretaceous coal seams) effectively saturating (and continually replenishing) the entire volume of pore space in the surrounding Deep Basin rock units (Welte et al., 1984). Up dip, natural gas leaks out of the Deep Basin and into conventional petroleum systems at a rate not exceeding that of Deep Basin gas generation (Varley, 1984; Masters, 1984C). As the basin ages and begins to rebound the capillary controlled up dip gas-water transitions begin to migrate back towards the progressively shallowing basin-center (Law, 2002). Inevitably the basin is either rejuvenated or the formations water out.

Also revealed was that many of the lower Cretaceous producing formations (including the Cadotte Member of the Peace River Formation) are characterized by sediments deposited along sand-rich coastlines with less common, laterally discontinuous accumulations of well-sorted gravel (Jackson, 1984; Smith et al., 1984). These sediments have been buried to great depths and have undergone various forms of diagenesis. The sandstones are dominantly well-sorted, fine-grained, quartz arenites. These quartz arenites have been subjected to intense silica cementation (quartz overgrowth development) resulting from pressure solution along grain contacts associated with their deep burial depths (Figure 1.10A)(Hutcheon, 1990). These overgrowths effectively sealed pore throats and destroyed permeability, thereby trapping the Deep Basin gas in a "tight framework" (Figure 1.11). Less common, well-sorted, chert-rich coarse sand and conglomerates that have been subjected to the same pressure and depth conditions as the quartz sandstones, developed a thin halo of small euhedrally terminated quartz crystals known as druse (Cant, 1986)(Figures 1.10B and 1.11). Since the druse is commonly not thick enough to seal off the larger pore throats of the well-sorted, coarse-grained, chert-rich sediments, thick preserved coastal accumulations exhibiting these characteristics represent the best gas reservoirs in the Deep Basin (Masters, 1984C)(Figure 1.12). In essence, the problem with the Deep Basin isn't finding gas, it's finding permeable rock that it can be economically produced from.

In 1986, Canadian Hunter continued to delineate the Deep Basin edges for different economically significant Formations and Members (including the Cadotte), and found themselves moving northwest of Elmworth into British Columbia. They spudded their first B.C. Deep Basin well at Noel, and it "penetrated a thick section of gas saturated conglomerates and sandstones" (Hayes, 1988). As more petroleum companies successfully expanded into the greater Noel area other significant Cadotte fields were discovered and the potential for more untapped accumulations of gas in Cadotte reservoirs was starting to be realized.

Estimates from Reinsen et al. (1993) indicated that 9 years ago 53.2 trillion cubic feet of gas remained undiscovered in lower Cretaceous strata of the Western Canadian Sedimentary Basin. This number is much smaller today; however, a significant volume of potential gas is still contained in lower Cretaceous formations geographically located within the confines of the Canada's Deep Basin. Therefore, an increased understanding of the behavior of the genetically related depositional systems responsible for the distribution of reservoir quality sediment could decrease difficulties encountered during exploration and production.

1.5 Age and Stratigraphic Nomenclature

The stratigraphic nomenclature for the Cadotte Member of the Boulder Creek/Peace River Formations has had a long and dynamic history. Confusion arises from the independent evolution of both the Boulder Creek and Peace River Formations, and the different type localities associated with each. The evolutionary paths, and type localities, have been chronologically summarized below in the hopes of clarifying the abundance of names that have been applied to rock units belonging to what is now accepted, both at surface and within the subsurface, as the Cadotte Member. The nomenclature of Gibson (1992) will be used in this thesis.

In 1893, R.G. McConnell recognized sandstones underlying the Fort St. John shales along the Peace River and named them the Peace River sandstones (part of the lower Cretaceous Fort St. John Group). McLearn (1917) interpreted these Peace River sandstones as being correlative with the lower Cretaceous Bullhead Mountain Formation. This was due to their similar stratigraphic position. Spieker (1921), while mapping in the Pine River valley (south of the Peace River valley, northeast British Columbia), came across sandstones and conglomerates outcropping at the mouth of Commotion Creek (Figure 1.4). He named this unit the Boulder Creek conglomerate, which he also assigned to the Bullhead Mountain Formation. Later, Wickenden and Shaw (1943) recognized that these rocks were, in fact, younger than the Bullhead Mountain Formation and redefined them as part of the Commotion Formation (Table 1.1). They assigned the outcrop at Commotion Creek, as well as an outcrop along Hasler Creek, as the Formation's type localities.

In the eastern Peace River valley Wickenden (1944) informally subdivided McConnell's (1893) original Peace River Sandstone into four members. In ascending order these members consisted of a basal member, middle shale member, Cadotte member and an upper continental member. The three descriptive members weren't given official names in the hope that future work would allow for more regional correlation, at which time more suitable geographic names could be assigned. In 1954, the Alberta Study Group reviewed the nomenclature for the Peace River Formation and formally defined three members: the middle shale Harmon Member, the marine sandstone Cadotte Member and the continental Paddy Member (Wickenden's basal member became the Notikewan Member of the Spirit River Formation). Stelck (1958) addressed the correlation of the Cadotte Member with the Viking Sand (a petroleum-bearing unit of eastern Alberta) and determined that the Cadotte and Viking had distinct faunal assemblages. He demonstrated that both the Viking sand and underlying Joli Fou shale faunal assemblages showed a greater similarity to the faunal assemblage of the marine portions of the Paddy Member than that of the Cadotte. He concluded that the Paddy represented "the shoreline phase of the upper part of the Joli Fou section plus an abbreviated portion of the Viking interval." This correlation was supported by cross-section correlations done by Oliver (1960).

In 1961, Stott (1961B) revisited the Commotion Formation type localities and determined that the sections were incomplete. He therefore proposed two reference sections, one at Dokie Ridge and the other at Bullmoose Mountain. The strata at Dokie Ridge were interpreted as entirely marine, while Bullmoose Mountain consisted of both marine and non-marine strata.

Stott (1960, 1961A, 1961B, 1962, 1968) undertook numerous studies of lower Cretaceous strata in the Canadian Rocky Mountains, during which he informally designated three members of the Commotion Formation. He described the lowermost Gates Member as consisting of fine sandstone, carbonaceous shale and coals of both marine and non-marine origin. Abruptly overlying the Gates are shales of the middle Hulcross Member, while marine to nonmarine, fine to coarse-grained sandstones and conglomerates of the upper Boulder Creek Member cap the succession. These members of the Rocky Mountain Foothills were then correlated to the Peace River plains, and it was determined that the Gates Member was correlative with the Spirit River Formation, while the Hulcross and Boulder Creek Members were correlative with the Peace River Formation (Stott, 1961B, 1962). Later, Stott (1982) elevated the Gates, Hulcross and Boulder Creek Members to Formation status (Table 1.1). In 1992, Gibson further subdivided the Boulder Creek Formation into an upper, coal-bearing Walton Creek Member (correlative with the Paddy Member of the upper Peace River Formation) and the lower, marine Cadotte Member (Table 1.1). This nomenclature was used in the study.

According to Yanagi et al. (1987) the Albian Stage represents a time period from 107-95 Ma, with the middle Albian being between 103 and 99 Ma. Within the confines of time exist numerous biostratigraphically significant temporal zones. This zonation and its respective relationship within Albian stratigraphy are outlined in Table 1.1.

The ammonite *Pseudopulchellia pattoni* Imlay, recovered from the Hulcross Formation at Commotion Creek (Figure 2.15A), allows for correlation with existing biostratigraphic Ammonite Zones. This ammonite is the namesake of the second oldest, of four middle Albian Ammonite Zones presented and defined in Jeletzky (1980) and Caldwell et al. (1993), and is exotic with respect to northeast British Columbia. Stelck (1995) interprets it as more common to the Arctic Sverdrup Basin. *Pseudopulchellia*'s age assignment of middle Albian is supported by a radiometric age of approximately 102.4 Ma obtained by Yanagi et al. (1987) from a tuff bed near Hudsons Hope, contained within the upper portions of the of the Hulcross Formation (at the *Haplophragmoides multiplum* Microfaunal Subzone type section). Stelck (1995) has also recovered *Gatsroplites kingi* McLearn from sandstone beds of the lower Cadotte at Commotion

Creek, indicating a conformable transition from the Hulcross Formation to the Cadotte Member and an age of middle Albian.

A discussion regarding surfaces of temporal significance within and overlying the Cadotte will be presented at the end of this chapter.

1.6 Paleogeography

Caldwell (1983) poetically describes the Cretaceous Period as having "spanned a time when vast new rift systems developed, sea-floor spreading was exceedingly rapid, large numbers of seamounts came into existence, and there were dramatic changes in the directions and rates of continental drift." These global tectonic regimes also controlled more localized tectonic events prevalent along continental margins. Global sea-level curves produced by Haq et al. (1987 and 1988) suggest that the middle Albian Earth was experiencing an eustatic state of sea-level rise (Figure 1.13). Jeletzky (1978), however, emphasized that the maximum amplitude of eustatic sea level variations is much less than the minimum amplitude of short-term localized vertical tectonic movements. Due to the causative link between the Western Canadian Foreland Basin and its westerly bounding Cordilleran Orogen, the history of relative sea-level fluctuations within the Western Canadian Sedimentary Basin was therefore dominated by local tectonic activity (Underschultz and Erdmer, 1991; Cant and Stockmal, 1993). To further support this argument, the time period during which the Hulcross Transgressive-Regressive couplet was emplaced has no obvious expression on the sea-level curve of Haq et al. (1987 and 1988)(Caldwell, 1983).

Paleopole reconstructions for the middle Albian reveal a pole located in the vicinity of 71°N,164°W, approximately 19° south of its current location and just off the northern coast of present day Alaska (Figure 1.14)(Irving et al., 1993). It was during this time that a Boreal marine incursion flooded a large portion of northern Alberta and northeast British Columbia to an approximate present day limit of 54° north latitude. This incursion formed an epicontinental (Hulcross) sea, which deepened to the west and north (Figures 1.14 and 1.15). Stelck et al. (1956) cited the presence of species of the *Haplophragmoides multiplum* foraminiferal subzone (Table 1.1) recovered from shales of the conformable, stratigraphically older, Hulcross Formation as indicative of a sea with normal salinity, minimal oceanic connections, and a depth in excess of 100 feet. The minimal ocean connections were due to the development of a series of straits located between the Arctic Sverdrop and the Western Canadian Sedimentary Basins (Stelck, 1995). These straits limited the migration of ammonite species from the Arctic into northern British Columbia and Alberta, and allowed for the evolution of an "endemic assemblage" which occasionally contained a somewhat more exotic species (Stelck, 1995).

Loyd (1982) attempted to reconstruct Mid-Cretaceous ocean circulation and surface temperature for a linked Boreal and Gulfian Western Interior Seaway. He concluded that at northern latitudes, ocean surface temperatures ranged from 14-16°C during winter months and 22-24°C during summer months. Although these estimates are for a linked seaway (similar to that of overlying Paddy Member deposits), undoubtably warmed by Gulfian marine waters, they provide an approximate maximum ocean surface temperature for middle Albian waters, as it is unlikely that Boreal sea surface temperatures alone would exceed these values. The values are also of relevance in that they provide evidence of seasonal temperature variations. Seasonal variations would profoundly effect atmospheric circulation and the development and cyclicity of severe storm systems. Hurricane development and periodicity is commonly linked with months/years of maximum sea surface temperatures (Gray, 1984). A hurricane requires high surface water temperatures to drive the rapid rate of evaporation required to set up and maintain the fundamental barometric contrasts necessary to support the storm (Barron, 1989). Modern hurricane generation commonly occurs at sea surface temperatures above 26-27°C, slightly higher than Loyd's (1981) estimates for a Mid-Cretaceous sea. Barron (1989) argues against hurricane domination in the middle Albian as, the unlinked Hulcross sea would most likely geographically isolate northern regions with respect to hurricane penetration from their equatorial sources. As hurricanes are generally associated with late spring to early autumn, winter storms are inherently linked with winter. Severe winter storms are controlled by thermal contrasts between oceans and continents where there is the "closest juxtaposition of cold and warm air masses" (Barron, 1989). During the Lower Cretaceous, an unlinked Canadian Boreal Sea would be more susceptible to winter storms (Marsaglia and Klein, 1983; Duke, 1985). These storms would have migrated east from their place of origin along the Eastern Asian seaboard, across the northern Pacific Ocean and into the Western Canadian Boreal Hulcross Sea (Barron, 1989)(Figure 1.14).

Cadotte sedimentary accumulations have been consistently interpreted as high energy shorefaces and deltas which have been subjected to frequent storm reworking (Either, 1982; Stott, 1982; Masters, 1984C; Moslow and Pemberton, 1988). High resolution detailed facies modelling has led authors to further constrain Cadotte shorelines as being indicative of a barred state complete with well-developed longshore and rip channel systems, drawing analogies to the southwest coast of Oregon (Hunter et al., 1979; Smith et al., 1984; Rhamani and Smith, 1988; Gibson, 1992; MacEachern, 1994; Saunders et al., 1994). The abundance, if not dominance, of storm-related sedimentary structures (Hummocky and Swaley Cross Stratification), highly winnowed sediment and multiple erosionally amalgamated storm beds attest to the strong storm influence Cadotte shorelines experienced (MacEachern, 1994). Saunders et al. (1994) and MacEachern (1994) have emphasized the seasonal cyclicity of storm systems, and have hypothesized that Cadotte shoreline progradation would have been the result of a combined fairweather summer profile (non to weakly barred state) overprinted by a storm dominated winter profile (barred state).

1.7 Structural Evolution

During the late Jurassic the western margin of the North American craton underwent a drastic change in basin configuration. This change represented the transition from a divergent, passive margin miogeoclinal platform dominated by shallow marine carbonate accumulations, to a convergent Andean-type margin with both an orogenic belt

(Cordilleran Orogen) and its associated Foreland (Rocky Mountain Fold and Thrust Belt and Western Canada Sedimentary Basin)(Kauffman, 1984; Poulton, 1989; Cant, 1989). The Cordilleran Orogenic Belt formed in response to terrane accretion and subduction processes along Canada's western margin. It consists of a series of smaller structurally and mineralogically complex tectonic belts characterized by varying degrees of igneous, metamorphic and sedimentary rocks (Figure 1.16)(Monger et al., 1982; McMechan and Thompson, 1989). The Columbian Orogen is a smaller region of uplift located along the eastern margin of the Cordilleran, the eastern edge of this orogen bordered the western deposition basin (Figure 1.15)(Stott, 1975). It experienced two major episodes of orogenesis, the first between the Late Jurassic to Earliest Cretaceous (Berriasian-Valanginian) and the second, during which the Cadotte was deposited, Early to Late Cretaceous (Barremian to Cenomanian)(Stott, 1983). This tectonism provided a large siliciclastic sediment source able to feed subsequent deposits in the easterly adjacent Foreland Basin (Williams and Stelck, 1975; Stott, 1982; Cant, 1989).

Formation of the Foreland Basin has been attributed to downward lithospheric flexure formed in response to the downward force created during accretion of allocthonous terranes to the craton's western margin, and is intimately linked with the growth of the Canadian Cordilleran and Foreland Fold and Thrust Belt (Monger and Price, 1979; Underschultz, 1991). The easternmost tectonic belt, the Foreland Fold and Thrust belt (consisting of the Rocky Mountains and Rocky Mountain inner and outer Foothills) bounds the current Western Canadian Sedimentary Basin along its western margin (Figure 1.16). Along this margin, eastward expansion and migration of both the Cordilleran, and the Foreland Fold and Thrust Belt, led to crustal thickening and extensive loading as large volumes of structurally displaced igneous, metamorphic and sedimentary rocks began to be piled on top of one another. The basin responded to this overthickenning by downwarping its underlying crust, the magnitude of which was greatest along this tectonically active western flank (Beaumont et al., 1993). The differential subsidence of the basin's crust created its large eastward tapering shape, characteristic of foreland basins, while a Deep Basin formed along its western margin (the area that had undergone the greatest magnitude of subsidence) (Figure 1.17) (Jackson, 1984).

The propagation of the fold and thrust belt was characterized by periodic uplift and subsidence, both of which would heavily influence local relative sea level fluctuations, subaqueous shelf gradients, erosion rates, control weather patterns and exert force strong enough to bend and break portions of Western Canada's crust. A tectonic event has been attributed with the emplacement of the large Lower Cretaceous Mannville Group, of which the Cadotte can be considered a part, and has been classified as an Exxon-type third order cycle - encompassing a period of time between 10 and 100 million years (Plint et al., 1992; Cant, 1996). Cant (1996) attributes the multiple Fahler, the Notikewan and Cadotte Members to Exxon-type fourth order cyclicity (occurring on an order of 1-10 million years)(Plint et al., 1992).

Deformation continued during the late Cretaceous to Tertiary Laramide Orogeny. This orogenic event is responsible for much of the structural displacement and deformation now evident in the Foothills Fold and Thrust Belt (Leckie, 1989). Westward dipping thrust faults continued migrating from west to east and converged down into a basal detachment, overlying an non-thrust faulted basement, characteristic of thin-skinned deformation (McMechan and Thompson, 1989). Coupled with folds, they occur in a variety of sizes and concentrations and can be used to subdivide the Foreland Fold and Thrust Belt into three segments, the "southern (thrust-dominated), central (transitional) and northern (fold-dominated) segments" (McMechan and Thompson, 1989). Both the Commotion Creek and Dokie Ridge study areas are located in the central transition segment. This segment is characterized by a transition from a thrust dominated to fold dominated style of deformation and is bordered at its eastern extent by a low-taper triangle zone (Figure 1.3) (McMechan, 1985). Hughes, (1967) further subdivided the foothills portion of the central segment into inner and outer zones (Figure 1.3). Dokie Ridge lies within/along the eastern margin of the western inner foothills (characterized by close faulting and folding), while Commotion Creek lies in the eastern outer foothills (containing more wide, low amplitude synclines, separated by narrow faulted anticlines) (Figure 1.3)(Hughes, 1967). McMechan (1985) has estimated the total amount of shortening incurred by Upper Triassic to Upper Cretaceous strata in the Pine River valley to be approximately 13 km. More locally, Bienia (1982), after completing a coal exploration study specifically dealing with Gulf Canada's Trefi prospect area (within which the Commotion Creek study area lies) made an estimate of 800 m of eastward displacement incurred by the Boulder Creek Formation's Walton Creek Member. This suggests that both the Commotion Creek and Dokie Ridge study areas are located in positions proximal to their original depocenters.

1.7.1 Peace River Arch/Embayment

Smaller tectonic structures also influenced the location and orientation of Cadotte deposits. A major structurally active region known as the Peace River Arch/Embayment is located east-northeast of the study area (Figure 1.15). During the middle Cretaceous the Peace River Arch was subsiding, which resulted in a localized depocenter termed the Peace River Embayment (O'Connell et al., 1990), upper Mannville sub-basin (O'Connell et al., 1990) and the Clearwater Shale Basin (Jackson, 1984). Regardless of the basin's name, it represented a large hole in a location proximal to a major potential sediment source, and subsequently, exerted a large influence over the distribution and orientation of local sedimentary accumulations. Subsidence steepened local shelf gradients and led to coastal flooding (transgression). Cant (1989) attributes continued subsidence of the Peace River Arch with flooding the Notikewan and allowing continuous deposition of Harmon/Hulcross shales. By this reasoning, it may be postulated that periods of prolonged Arch quiescence would allow for continuous and extensive basinward progradation of coastal complexes (as evident in Cadotte distribution) while short lived alternating periods of subsidence and quiescence would lead to increased vertically stacked coastal deposits (evident in the underlying Fahler's distribution).

Much of the Middle Cretaceous subsidence associated with the Peace River Arch is attributed to the Dawson Creek Graben complex (approximately centered on the Arch), which had renewed its subsidence, leading to the development of localized deep basin conditions (O'Connel et al., 1990). The arcuate east to west orientation of the southern boundary of this graben complex exerted a significant facies and shoreline orientation control on the distribution of the Cadotte Member (Figures 1.15 and 1.17). Stott (1982) noted the transition of Cadotte sediment from conglomerates and sandstones south of the southern edge of the Dawson Creek Graben Complex, to siltstones and shales north of it (Figures 1.15 and 1.17). Leckie et al. (1990) constructed regional isopach maps of the Cadotte Member and found that it thickened to the northwest (a zone characterized by a deeper basin coincident with potential western extension of the Dawson Creek Graben Complex) and thinned rapidly (from 40 to <3m) at its northern boundary over a basinward distance of approximately 4 km (coincident with the southern boundary of the Dawson Creek Graben Complex). As well, these maps showed a preferred east-southeast/west-northwest trend in sediment thickness that is also mimicked by hydrocarbon pool mapping of conglomerate distribution in the Deep basin (Figure 1.12). These trends represent the orientation of Cadotte shorelines parallel to the orientation of the graben complex's southern margin.

1.7.2 Commotion Creek Local Structure

The Commotion Creek study area is characterized by a shallow, broad, concentrically folded parallel anticline (Figure 1.5). The surface exposed anticline trends approximately northwest/south southeast. This structure is cut by occasional east dipping thrust faults (the trends of which roughly parallel the trend of the anticline). These small faults formed synchronously with the larger, Commotion Creek structure (Hughes, 1967). The development of the anticline is schematically illustrated in Figure 1.18. The prominent nature of Cadotte conglomerates and coarse sandstones, outcropping as vertical cliff faces in and adjacent to the creek valley, outline the broad, shallow nature of the structure's east and west limbs, while the crest of the fold has been subjected to intense erosion and removal associated with a higher component of fracturing. The east and west limbs of this anticline dip at angles no greater than 14 degrees but average approximately 10 degrees and are themselves locally fractured (Figure 1.5 A). One major fracture is present within Commotion West and is interpreted to represent an eastward dipping minor thrust fault (Figure 1.5 B), however the vast majority of fractures do not penetrate the entire section of rocks. The numerous local fractures are interpreted to be the result of fracture formation taking advantage of previous planes of minor discontinuity (bedding surfaces and contacts)(Figure 1.5 C), as many of the fractures are either discontinuous within rocks of extremely similar, if not the same lithology; have orientations that are inconsistent with the orientation of structural features; can be explained rather simplistically by facies modeling; or are extremely asymmetric in orientation.

1.8 Present Day Distribution

Today the Cadotte is preserved throughout much of northwest Alberta and northeast British Columbia both at surface (Figure 1.3) and in the subsurface (Figures 1.15 and 1.17). Subaerial erosive edges bound the Cadotte along its northeast and south/southeast edges, while western erosion is associated with uplift and migration of the foothills deformation front. Isopach maps of Leckie et al. (1990) show that the northern extent of Cadotte progradation/distribution is coincident with the southern edge of the Peace River embayment (Dawson Creek Graben complex)(Figure 1.15). This northern limit marks a lithologic transition from coastal sands and conglomerates to offshore marine shales. The shale-out limit can be attributed to progradation into an extent of the basin where sediment supply and distribution could not adequately fill existing accommodation and was forced to a halt. The author can't help wondering what effect thick packages of sediment emplaced onto the margin of an active graben system may have had on Cadotte cyclicity. It may be that Cadotte shorelines were so successful in terms of their progradational extent that they were the architects of their own demise.

1.9 Cadotte in Space and Time – Unconformities and Previous Studies.

Global eustatic sea level curves constructed by Haq et al. (1987, 1988) show the middle Albian as being characterized by a state of eustatic sea level rise (Figure 1.13). Although undoubtedly sediment dispersal in the Western Canadian Sedimentary Basin was influenced to a much greater degree by more local factors, such as tectonic events occurring in the evolving western Canadian Cordilleran, and associated fold and thrust belt present along the basin's western margin (Cant and Stockmal, 1989; Underschultz and Erdmer, 1991; Pepper, 1994).

Cadotte sedimentation represents the accumulation of a large volume of siliciclastic sand and conglomerate in coastal areas, and is characterized by "rapid sediment supply rates into environments of high energy" (Either, 1982). The source of this sediment has been attributed to a complex assemblage of igneous, metamorphic and clastic rocks derived from the Omineca Crystalline Belt located along the western edge of the Rocky Mountain Trench (Figure 1.16)(Waddell, 1964). Leckie (1986) and Hyde and Leckie (1994) have drawn similar conclusions for sediment of the slightly older Gates Formation and younger overlying Paddy Member (both of which are lithologically similar). The authors note that the high quartz concentrations may also represent reworking of sediment derived from clastic units in the foreland fold and thrust belt (notably the Cambrian Gog and Precambrian Miette Groups).

Biostratigraphic studies conducted by Leckie and Stelck (1989), Stelck and Leckie (1990A and B) and Stelck (1995) have shown a difference in faunal assemblages of the marginal marine portions of the Paddy (Walton Creek subsurface equivalent) and Cadotte intervals, indicating a break in time between emplacement of the two sedimentary packages. Further, Leckie et al. (1989) and Leckie (1991A) have attributed the formation of multiple paleosols present in lower portions of the upper Boulder Creek Formation (Paddy/Walton Creek equivalent) in the Monkman Pass area as having developed during a state of relative sea level fall, when fluvial systems began to incise deep valleys and starve the alluvial/coastal plains of sediment. These paleosols, although of Paddy age, are important in that they may support an unconformable transition between the Paddy and Cadotte intervals (and hence, represent the expression of a sequence boundary beyond the confines of any incised valley systems). However Stelck (personal communication) emphasizes that this is in the Monkman Pass area and that the nature of the Paddy-Cadotte transition varies regionally.

Smith et al. (1984) pointed out that, genetically, it may be more accurate to avoid subdivision of the Boulder Creek Formation into 2 separate Members, as Gibson (1992) later did, because the Walton Creek Member (which at the time was known as the "upper carbonaceous facies" of the Boulder Creek Formation) probably just represented a nonmarine succession that was time equivalent with Cadotte shoreline deposits located further basinward.

These two viewpoints are important in any attempts to constrain the Paddy and Cadotte Members in a sequence stratigraphic framework because the presence of a sequence boundary directly overlying Cadotte marine sandstones and conglomerates implies a lack of accommodation on the coastal plain leading to sedimentary bypass, potential fluvial down cutting (creation of incised valley systems) and removal of underlying deposits (commonly associated with falling stage and lowstand systems tracts).

Further, regardless of whether or not a sequence boundary and its associated falling stage or lowstand systems tract is present in or above Cadotte sedimentary packages, a highstand situation must have been present following the shoreline transgression responsible for the emplacement of the underlying Hulcross Member offshore shales, as a relative sea level rise cannot go directly from a state of rising to falling without some turnaround point (e.g. stillstand conditions and therefore highstand)(Van Wagoner et al., 1990).

Interpreting the relative sea level state during which Cadotte sediments were deposited is further complicated by work done on the underlying Falher cycles (Spirit River Formation). The Falhers and the Cadotte members are characterized by similar coarse-grained deposits interpreted as representing emplacement and reworking in strongly wave dominated coastal settings (shorefaces) (Moslow and Pemberton, 1988; Moslow, 1998). Due to this similarity, it would seem probable that the two sedimentary packages share many common characteristics regarding their emplacement and distribution. The presence of a sharp erosive transition from coarse-grained, chert-rich upper shoreface deposits, to fine-grained, quartz-rich lower shoreface deposits commonly encountered in the Falher A, C and D cycles have been used by various authors to signify deposition during a falling stage of relative sea level, during which time the shoreline was in a state of forced regression (Arnott 1993; Cant, 1995; Caddel, 2000; Armitage, 2002). Caution must be taken, however, in applying Falher Member sequence stratigraphic models of emplacement to Cadotte systems, as regionally the Cadotte and Falhers behave very differently. The Falhers consist of multiple, vertically stacked cycles, which are not obvious in the Cadotte, as well; the Falhers are not as persistent in terms of basinward progradational extent (Figure 1.1). These are two important differences that cannot be overlooked, as regional sediment distribution patterns are intimately incorporated in the formation of a sequence stratigraphic model, and they tell us that relative sea level is behaving differently during emplacement of the Falher and Cadotte Members, even if some of the smaller scale autocyclic processes are not. Although a sharp transition is commonly evident separating Cadotte upper and lower shoreface deposits, in this thesis its formation has been attributed to the autocyclic process of bar emplacement and migration along a storm dominated coastline (Rhamani and Smith, 1988; Saunders et al., 1994; MacEachern, 1994) and not wave ravinement associated with a relative sea level fall (discussed further in Chapter 3).

The controlling process responsible for the creation of this sharp transition is important to exploration, as one model provides insight into where further upper shoreface (as well as reservoir quality, capping foreshore deposits) may be in relation to a hole that was just drilled (forced regression model), while the other only gives the geologist a better understanding about the characteristics of the shoreline complex that was just drilled.

MacEachern et al. (2002) attribute shoreline complexes in and around the Elmworth and Wapiti Fields to being emplaced during a state of relative sea level rise, suggesting a highstand systems tract. These deposits represent the initiation of sedimentation and the establishment of a progradational shoreline system following the transgression responsible for flooding of the Gates/Notikewan sandstones and emplacement of the Hulcross/Harmon shales. However, if the Cadotte were emplaced entirely during a relative sea level rise, the vast expanse of area and accommodation available for the formation of aggrading topsets may be difficult to continue to fill, while still providing enough sediment to the shoreline so that it may continue to prograde (Bertram and Milton, 1995). Therefore it is unlikely that highstand conditions were prevalent during the emplacement of the entire, basinwide, Cadotte sedimentary package.

A relative sea level fall of Cadotte age has been interpreted in the Noel gas field of northeast British Columbia as being responsible for fluvial incision and the formation of an incised valley system (Hayes, 1988). This system effectively removed portions of the older Cadotte shoreline complexes (possibly previous highstand deposits?) and presumably transported it to a falling stage/lowstand shoreline somewhere to the north/northeast.

In any case, the presence of a relative sea level fall may have helped to maintain the extremely successful basinward accreting nature of the Cadotte. One of the principle learnings concluded from this thesis is that constraining the Cadotte age shoreline complexes to one particular state of relative sea level is a far from simple or scientifically defendable exercise.

Table 1.1 – Stratigraphic nomenclature and associated biostratigraphic zonations of the Middle and basal Upper Albian. Nomenclature is shown for both B.C. Foothills and Peace River Plains; notice the presence and variation of the location, and temporal extent, of unconformities (red wavy boundaries). Nomenclature used in this report will follow that of Gibson (1992).

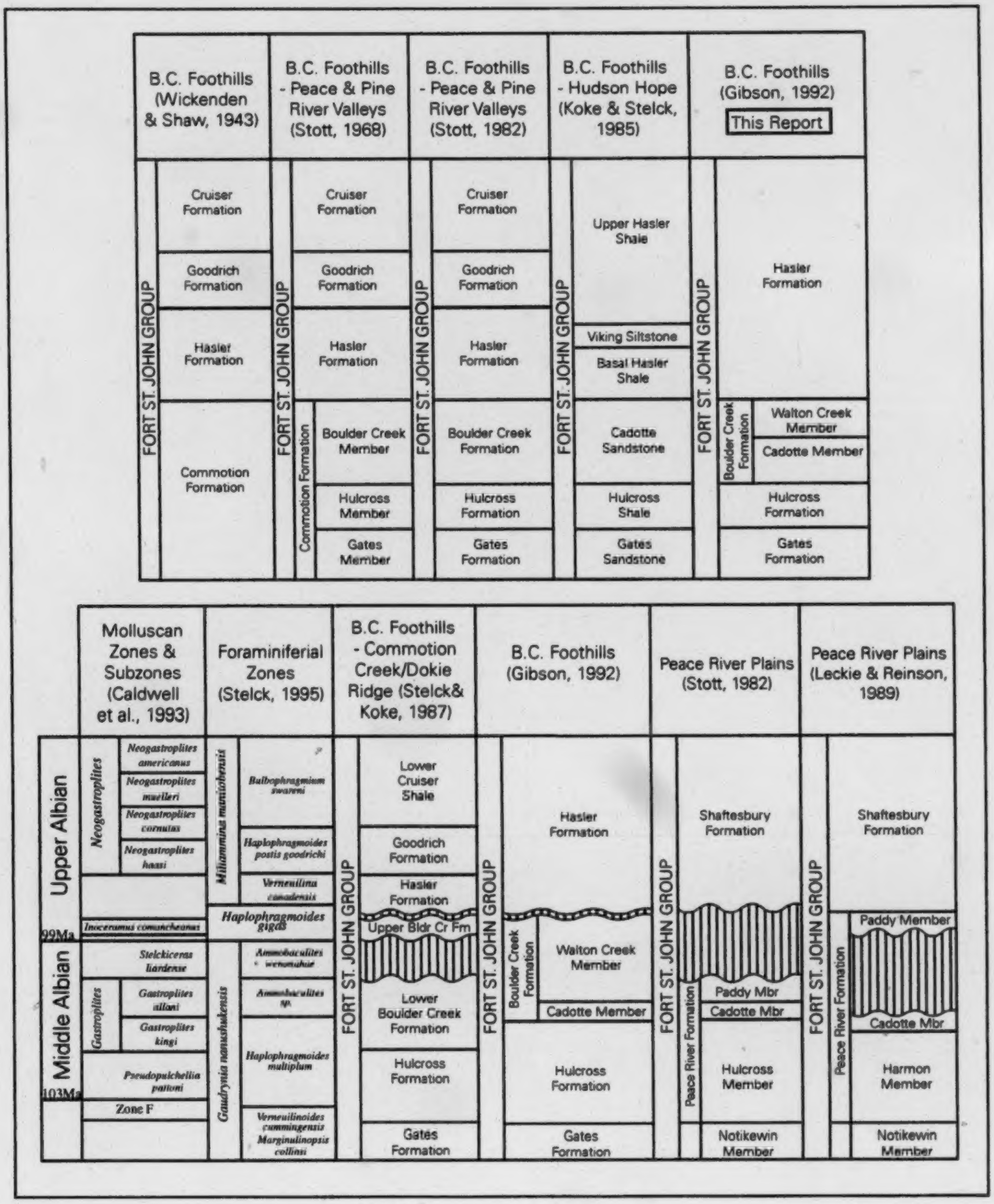

B.C. Foothills (Wickenden & Shaw, 1943)
B.C. Foothills - Peace & Pine River Valleys (Stott, 1968)
B.C. Foothills - Peace & Pine River Valleys (Stott, 1982)
B.C. Foothills - Hudson Hope (Koke & Stelck, 1985)
B.C. Foothills (Gibson, 1992)
This Report
FORT ST. JOHN GROUP
Cruiser Formation
Goodrich Formation
Hasler Formation
Commotion Formation
Boulder Creek Member
Hulcross Member
Gates Member
Boulder Creek Formation
Hulcross Formation
Gates Formation
Upper Hasler Shale
Viking Siltstone
Basal Hasler Shale
Cadotte Sandstone
Hulcross Shale
Gates Sandstone
Walton Creek Member
Cadotte Member
Molluscan Zones & Subzones (Caldwell et al., 1993)
Foraminiferial Zones (Stelck, 1995)
B.C. Foothills - Commotion Creek/Dokie Ridge (Stelck& Koke, 1987)
B.C. Foothills (Gibson, 1992)
Peace River Plains (Stott, 1982)
Peace River Plains (Leckie & Reinson, 1989)
Upper Albian
Middle Albian
99Ma
103Ma
Neogastroplites
Neogastroplites americanus
Neogastroplites muelleri
Neogastroplites cornutus
Neogastroplites haasi
Inoceramus comancheanus
Stelckiceras liardense
Gastroplites
Gastroplites allani
Gastroplites kingi
Pseudopulchellia pattoni
Zone F
Miliammina manitobensis
Bulbophragmium swareni
Haplophragmoides postis goodrichi
Verneuilina canadensis
Haplophragmoides gigas
Gaudrynia nanushukensis
Ammobaculites wenonahae
Ammobaculites sp.
Haplophragmoides multiplum
Verneuilinoides cummingensis
Marginulinopsis collinsi
Lower Cruiser Shale
Upper Bldr Cr Fm
Lower Boulder Creek Formation
Shaftesbury Formation
Peace River Formation
Paddy Mbr
Cadotte Mbr
Hulcross Member
Notikewin Member
Paddy Member
Harmon Member

Figure 1.1 – Northeastward tapering Lower Cretaceous clastic sedimentary wedge. Major sand packages are colored yellow and shales shaded gray. Diagram temporally outlines Clearwater and Hulcross trangressive-regressive couplets, and highlights the relative basin position of paleo-shorelines. Cadotte shoreline progradation followed a period of regional flooding (Hulcross/Harmon), shoreline progradation extended north to the southern margin of the Dawson Creek Graben complex. At this location, following a relative sea level rise, progradation occurred and deposition of the Walton Creek/Paddy occured. Note the vertical stacking nature of Gates intervals compared with laterally continuous Cadotte distribution. Outcrop nomenclature is illustrated in black, while subsurface nomenclature is dark blue, diagram modified from Stelck (1975) and Cant (1996).

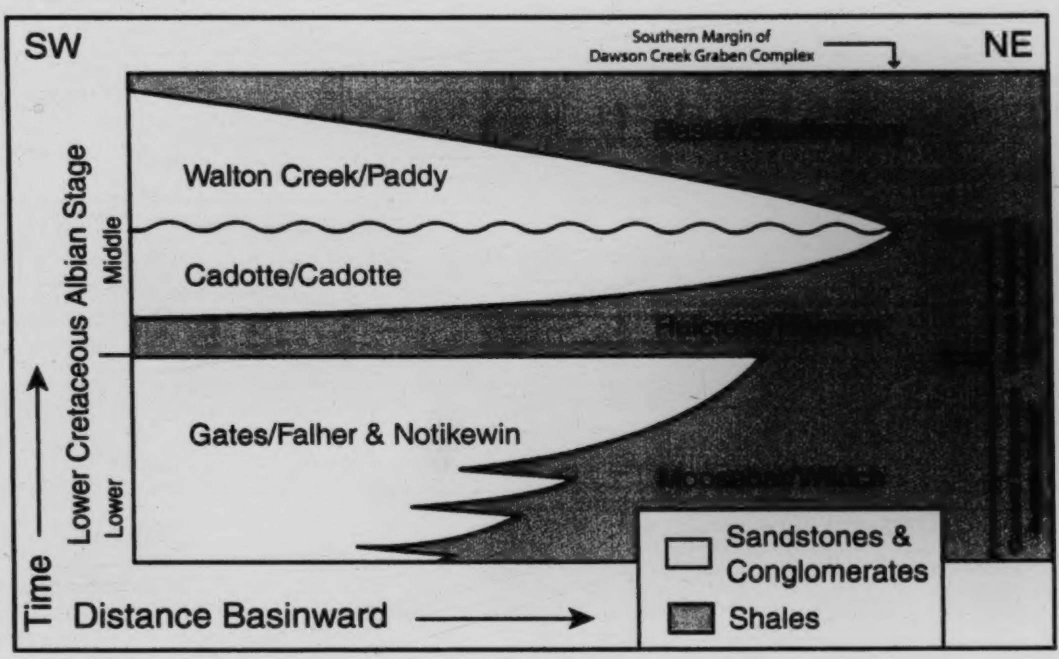

SW
Southern Margin of Dawson Creek Graben Complex
NE
Walton Creek/Paddy
Cadotte/Cadotte
Gates/Falher & Notikewin
Middle
Lower
Lower Cretaceous Albian Stage
Time
Distance Basinward
Sandstones & Conglomerates
Shales

Figure 1.2 – (A) Study area in a regional context. (B) Location of Commotion Creek and Dokie Ridge study locations near the town of Chetwynd in northeast British Columbia. Study drillhole location and pertinent Cadotte core locations also shown.

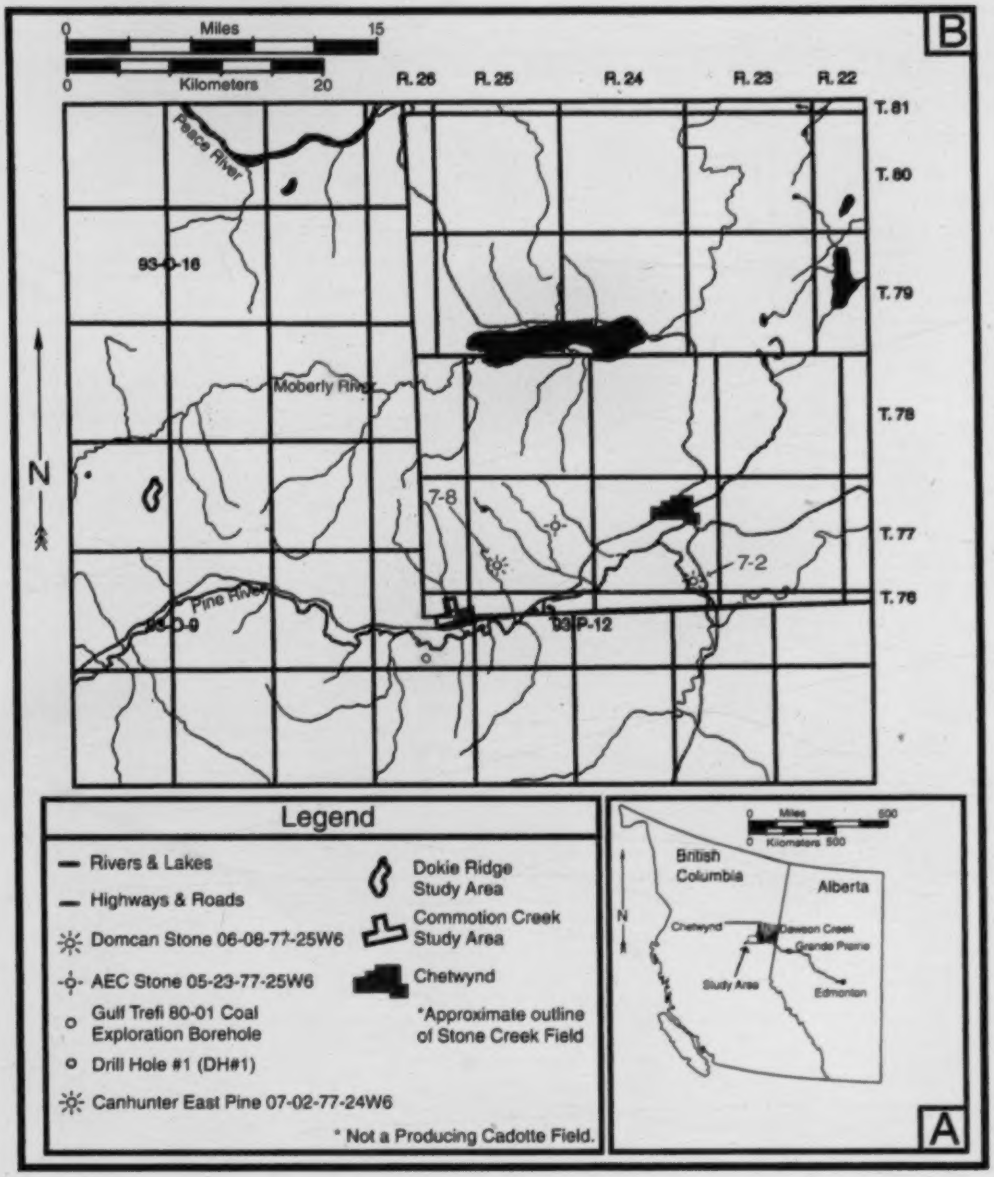

B
0
Miles
15
0
Kilometers
20
R. 26
R. 25
R. 24
R. 23
R. 22
T. 81
T. 80
T. 79
T. 78
T. 77
T. 76
Peace River
93-O-16
Moberly River
N
7-8
7-2
Pine River
93-O-9
93-P-12
Legend
Rivers & Lakes
Highways & Roads
Domcan Stone 06-08-77-25W6
AEC Stone 05-23-77-25W6
Gulf Trefi 80-01 Coal Exploration Borehole
Drill Hole #1 (DH#1)
Canhunter East Pine 07-02-77-24W6
Dokie Ridge Study Area
Commotion Creek Study Area
Chetwynd
*Approximate outline of Stone Creek Field
* Not a Producing Cadotte Field.
0
Miles
500
0
Kilometers
500
British Columbia
Alberta
N
Chetwynd
Dawson Creek
Grande Prairie
Study Area
Edmonton
A

Figure 1.3 – Geologic regional map and palinspastically restored cross-section. A) Map showing the regional structural setting around both study locations. Note the distribution of large scale structural subzones; Rocky Mountains, Inner and Outer Foothills. Map is an amalgamation of maps modified from McMechan (1985) and Stott (GSC Map - 1858A). B) Palinspastically restored cross section from McMechan (1985). Line of section is between A and B (located on map). Lower section represents current understanding of regional structural trends, and shows the blending of faulting and folding characteristic of the central transition segment of the Foreland Fold and Thrust Belt. Top section shows palinspastic restoration. Note the minimal amount of shortening associated with the development of the large, shallow and broad open folds (characteristic of the Outer Foothills) occurring in the Moosebar, Gates, Hulcross and Boulder Creek Formations.

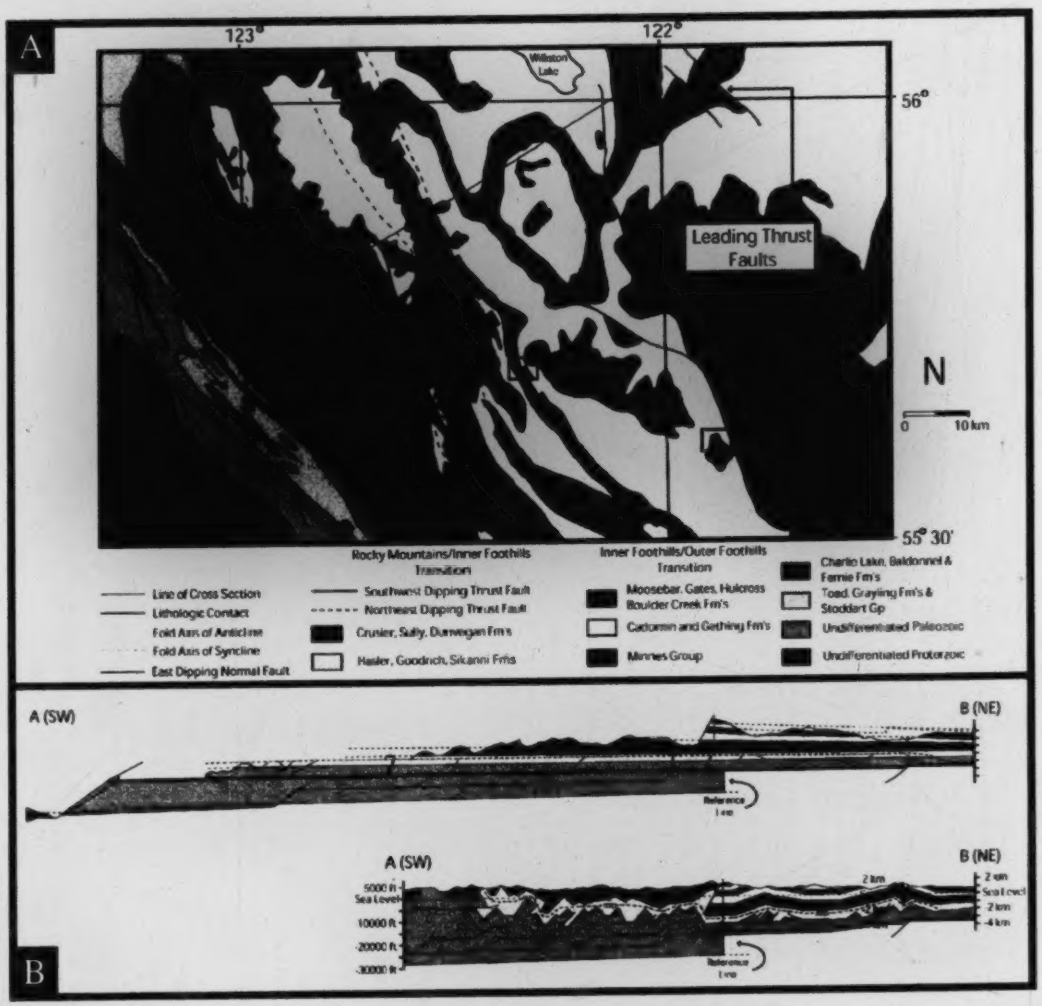

A
123°
122°
56°
55° 30'
Williston Lake
Leading Thrust Faults
N
0
10 km
Line of Cross Section
Lithologic Contact
Fold Axis of Anticline
Fold Axis of Syncline
East Dipping Normal Fault
Rocky Mountains/Inner Foothills Transition
Southwest Dipping Thrust Fault
Northeast Dipping Thrust Fault
Crusier, Sully, Dunvegan Fm's
Hasler, Goodrich, Sikanni Fm's
Inner Foothills/Outer Foothills Transition
Moosebar, Gates, Hulcross Boulder Creek Fm's
Cadomin and Gething Fm's
Minnes Group
Charlie Lake, Baldonnel & Fernie Fm's
Toad, Grayling Fm's & Stoddart Gp
Undifferentiated Paleozoic
Undifferentiated Proterozoic
B
A (SW)
B (NE)
Reference Line
5000 ft
Sea Level
10000 ft
-20000 ft
-30000 ft
2 km
Sea Level
2 km
4 km

Figure 1.4 – Panoramic photo mosaics of outcrop study locations. (A) Commotion Creek (upper) and Commotion West (lower) showing locations of vertically logged sections and prominent nature of conglomerate (major cliff forming in both mosaics). (B) Dokie Ridge looking to the Northwest showing outline and character of major stratigraphic boundaries. Cadotte conglomerate represents the most prominent lithology (relative to Hulross shales and silts, and Gates and Paddy sandstones).

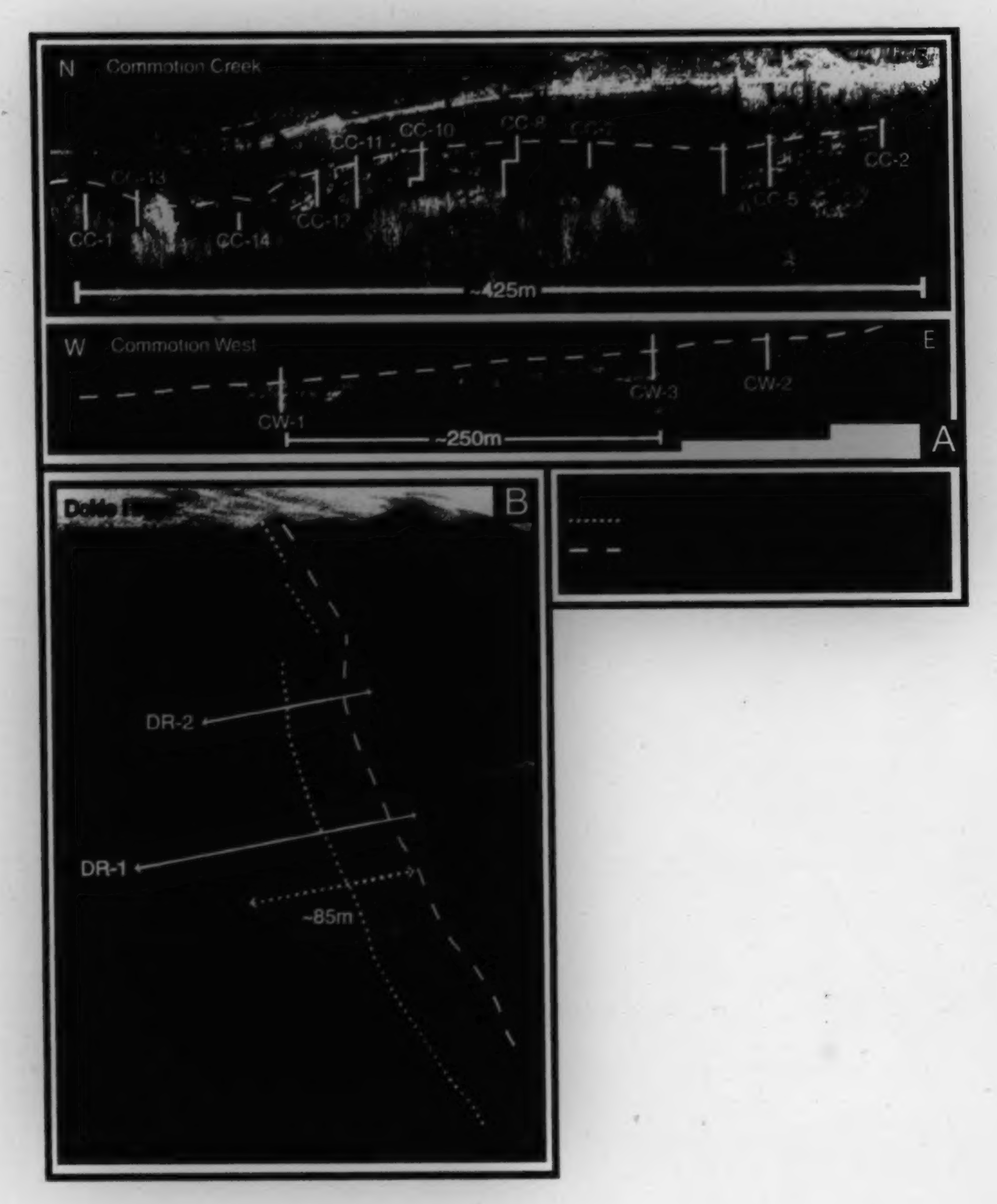

N
Commotion Creek
S
CC-13
CC-11
CC-10
CC-8
CC-7
CC-2
CC-1
CC-14
CC-12
CC-5
~425m
W
Commotion West
E
CW-3
CW-2
CW-1
~250m
A
Dolde
B
DR-2
DR-1
~85m

Figure 1.5 – (A) Panoramic of Commotion Creek anticline and location of study areas in reference to it. (B) Small east dipping thrust fault in Commotion West and (C) basinward (approximately north to northeast) dipping upper shoreface master bedset bounding surfaces in conglomeratic interval, at the head (northern end) of Commotion Creek.

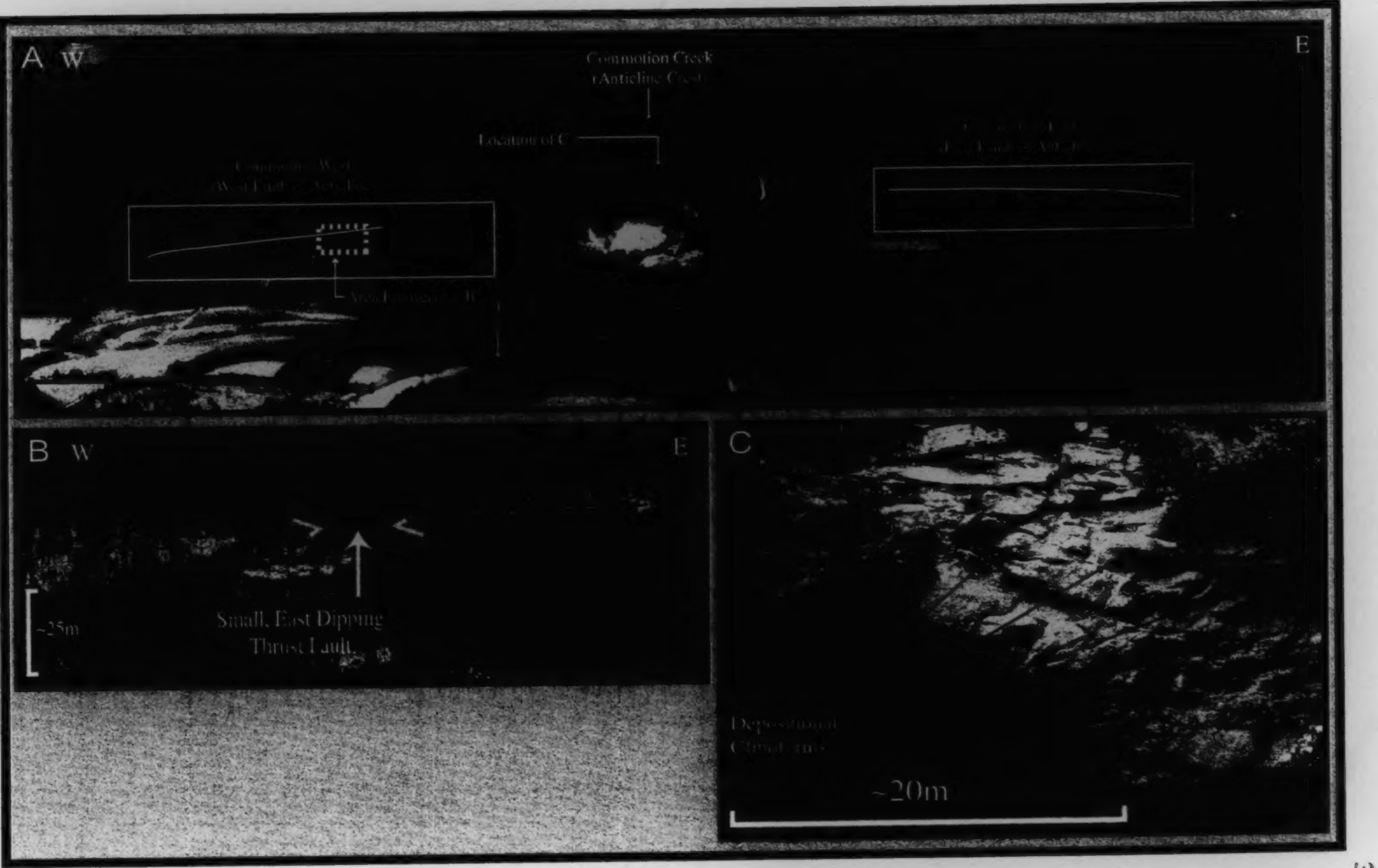

A W
E
Commotion Creek
(Anticline Crest)
Location of C
Commotion West
(West Limb of Anticline)
Area Enlarged in B
B W
E
~25m
Small, East Dipping
Thrust Fault
C
Depositional
Clinoforms
~20m

Figure 1.6 – Detailed outline of Commotion Creek and related study locations. Also note the trace of approximate derived paleo-shoreline strike as indicated from both swash lamination strike (planar seaward dipping beds in the forshore) and upper shoreface master bedset boundary dip directions.

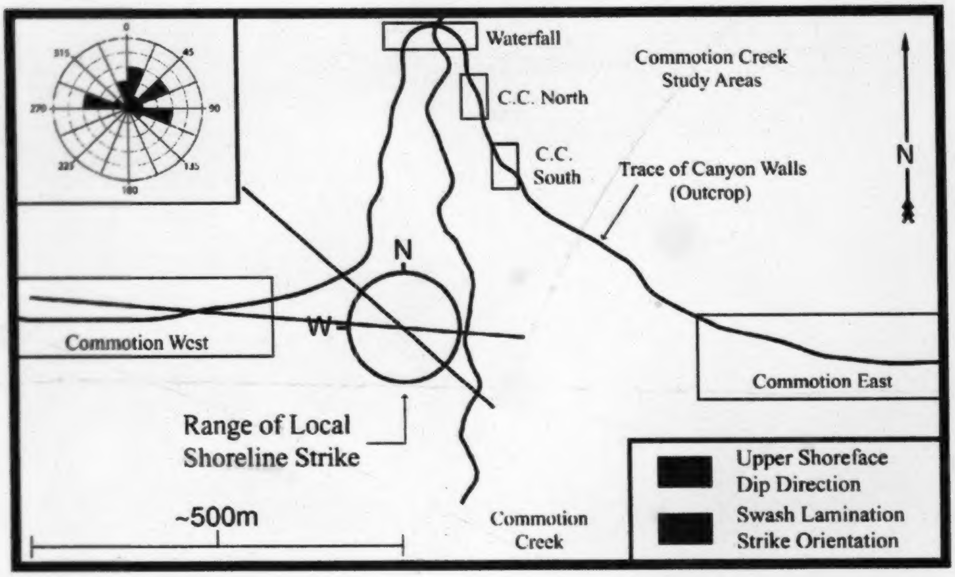

0
45
90
135
180
225
270
315
Waterfall
Commotion Creek
Study Areas
C.C. North
C.C.
South
Trace of Canyon Walls
(Outcrop)
N
N
W
Commotion West
Commotion East
Range of Local
Shoreline Strike
Upper Shoreface
Dip Direction
Swash Lamination
Strike Orientation
~500m
Commotion
Creek

Figure 1.7 – Location of conventional (blue) and Deep Basin type (red) gas pools and fields, with dashed line demarcating the boundary between them. Figure courtesy of BP Canada.

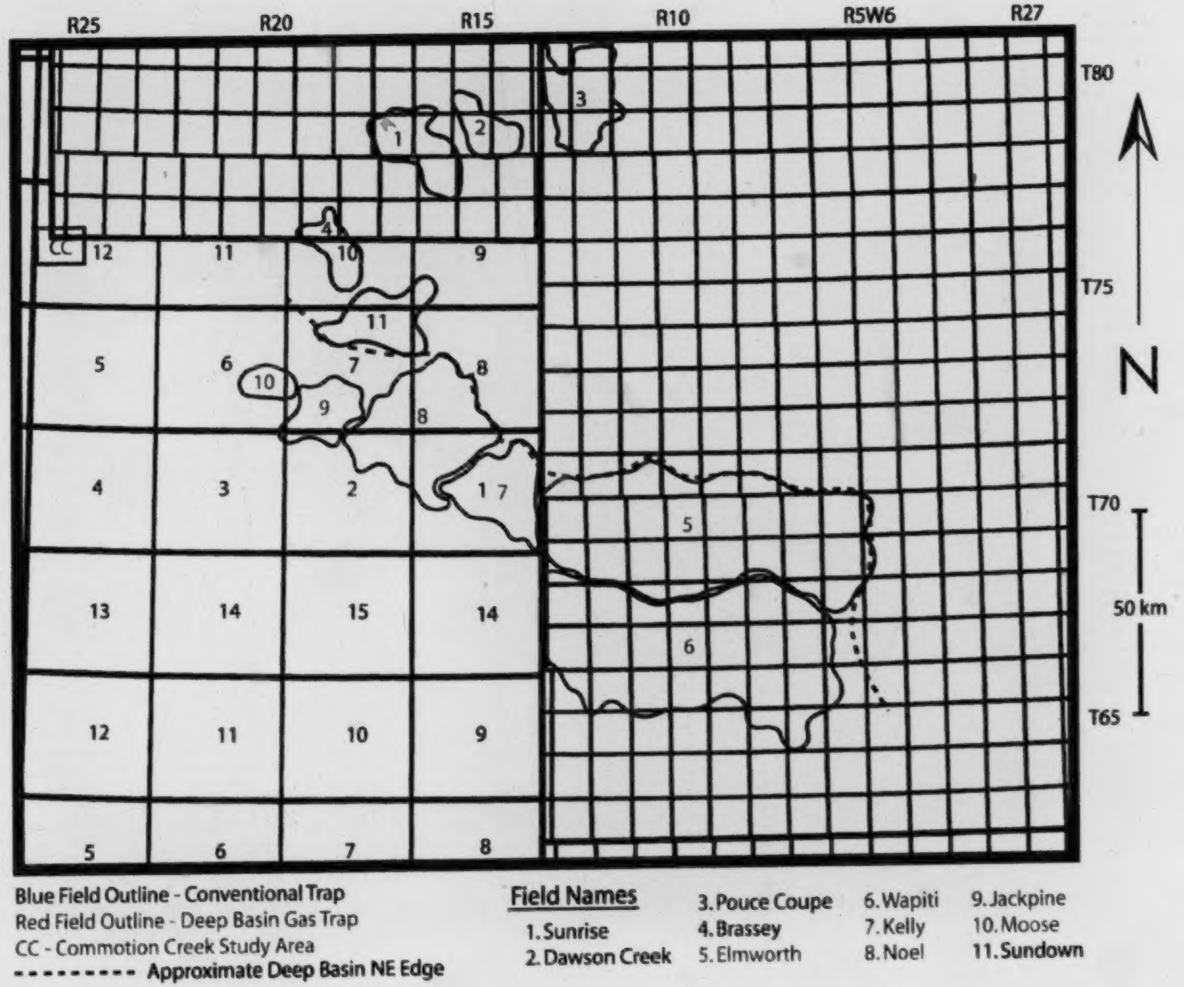

R25
R20
R15
R10
R5W6
R27
T80
T75
T70
T65
N
50 km
CC
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
17
Blue Field Outline - Conventional Trap
Red Field Outline - Deep Basin Gas Trap
CC - Commotion Creek Study Area
Approximate Deep Basin NE Edge
Field Names
1. Sunrise
2. Dawson Creek
3. Pouce Coupe
4. Brassey
5. Elmworth
6. Wapiti
7. Kelly
8. Noel
9. Jackpine
10. Moose
11. Sundown

Figure 1.8 – A) Anderson Water Wells drill rig during coring operations. B) Christensen 9-cutter coring bit (note the wear on the teeth due to the hard nature of the chert pebble Cadotte).

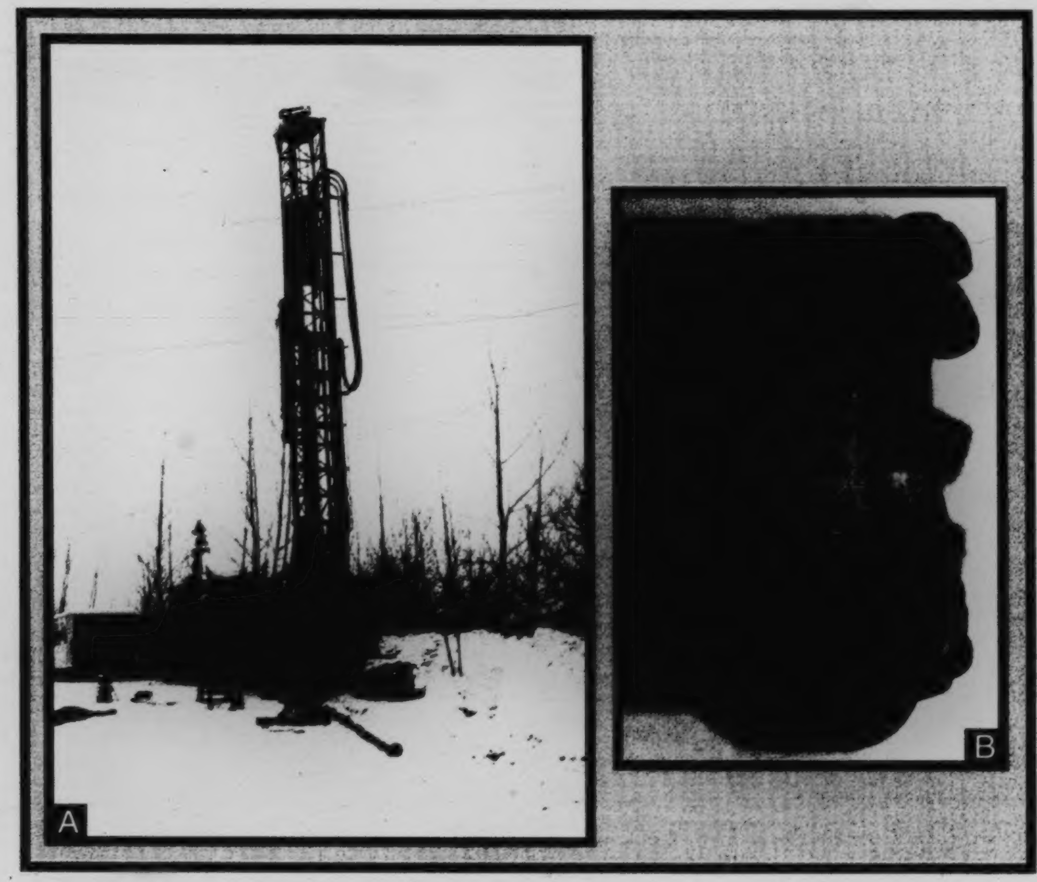

A
B

Figure 1.9 – Outline of Deep Basin with respect to disturbed belt (Foothills structural front) (from Masters, 1984B).

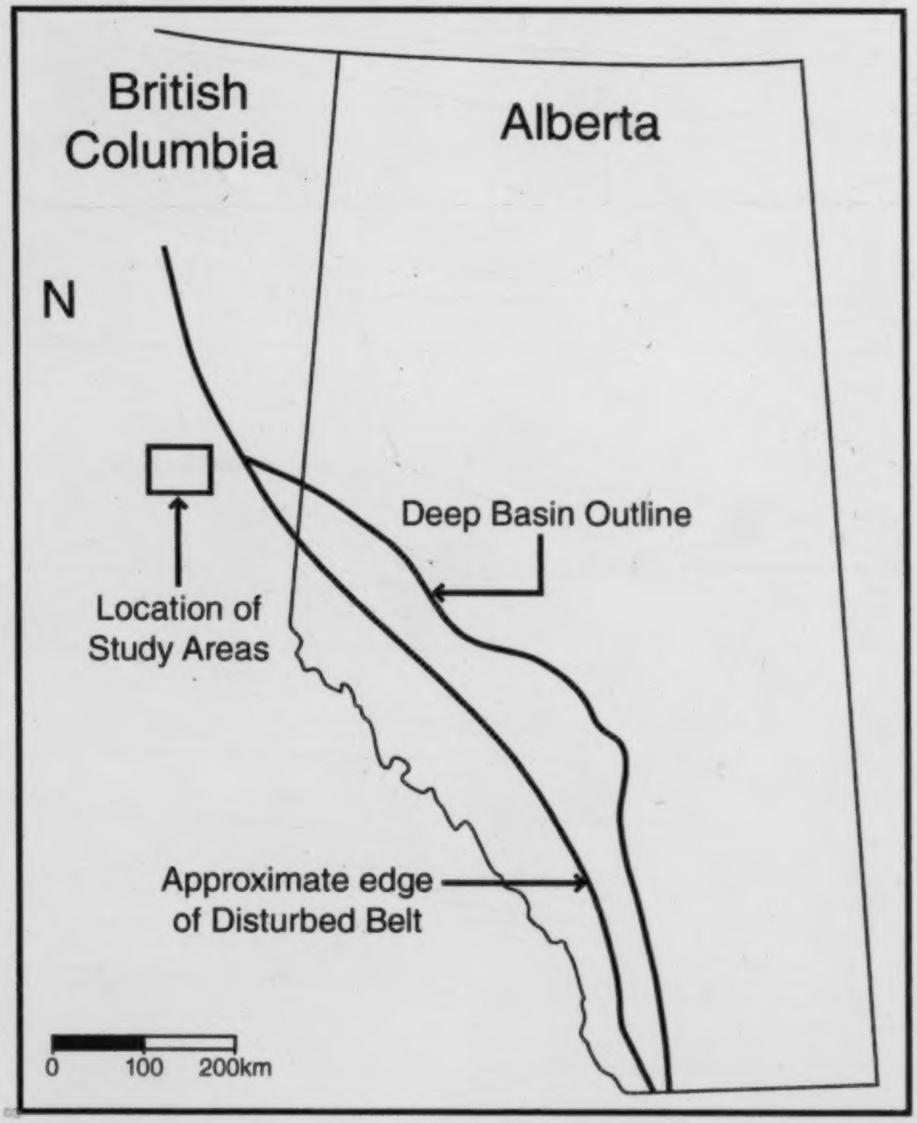
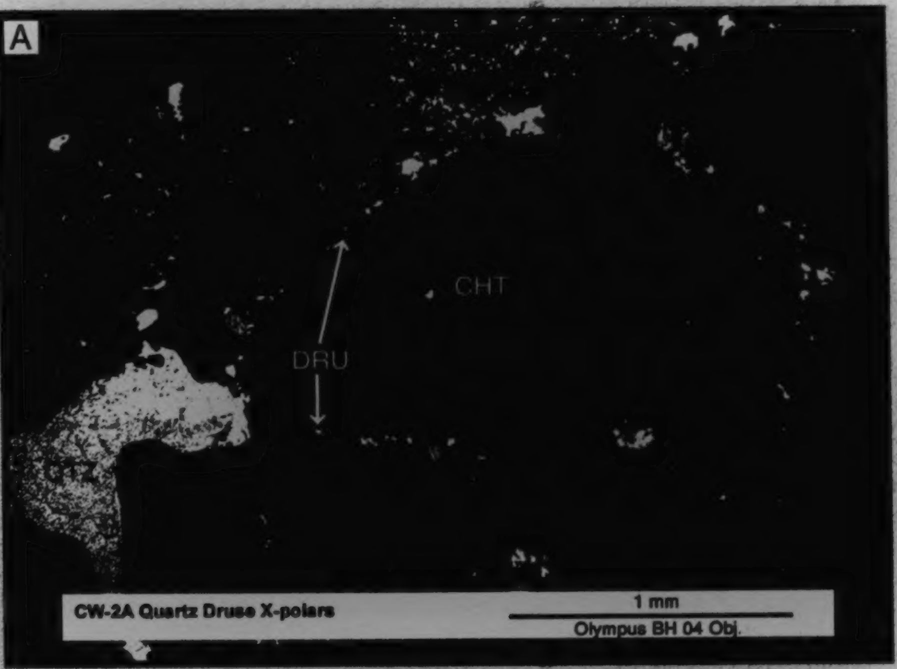
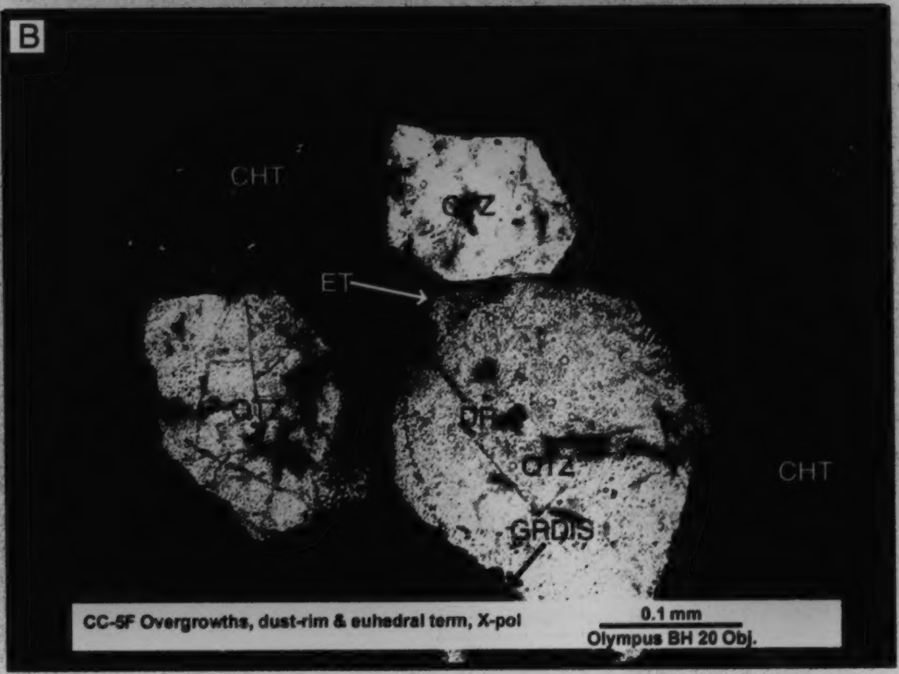

British Columbia
Alberta
N
Deep Basin Outline
Location of Study Areas
Approximate edge of Disturbed Belt
0
100
200km

Figure 1.10 – Diagenetic characteristics of chert conglomerates and quartz sandstones. Thin sections show styles of quartz cementation in chert conglomerates (A) vs quartz-rich sandstone (B) under crossed polars. Microcrystalline drusy quartz (DRU) on chert grain (A) and (B) Grain dissolution (GRDIS), dust rim (DR) and euhedral termination of quartz overgrowth (ET) on quartz sand grain.


A
DRU
CHT
QTZ
1 mm
Olympus BH 04 Obj.

CW-2A Quartz Druse X-polars


B
CHT
QTZ
ET
QTZ
DR
QTZ
GRDIS
CHT
0.1 mm
Olympus BH 20 Obj.

CC-5F Overgrowths, dust-rim & euhedral term, X-pol

Figure 1.11 – Diagram shows contrasting porosity and permeablity for variations in sediment grain size and sorting. Depositional relationships are shown on the left and diagenetic alterations are shown at right. Due to increased grain surface area fine, quartz-dominated sandstones have lower primary permeability than chert-rich pebble conglomerates. The conglomerates exhibit high permeability due to larger pore throat radii. Both well-sorted sandstones and conglomerates have higher porosity then less well-sorted sediment. Upon compaction, grain dissolution and cementation, chert grains develop drusy quartz rims while quartz grains develop quartz overgrowths. The coarse-grained nature of the chert helps preserve primary porosity while the finer quartz sands become tightly cemented.

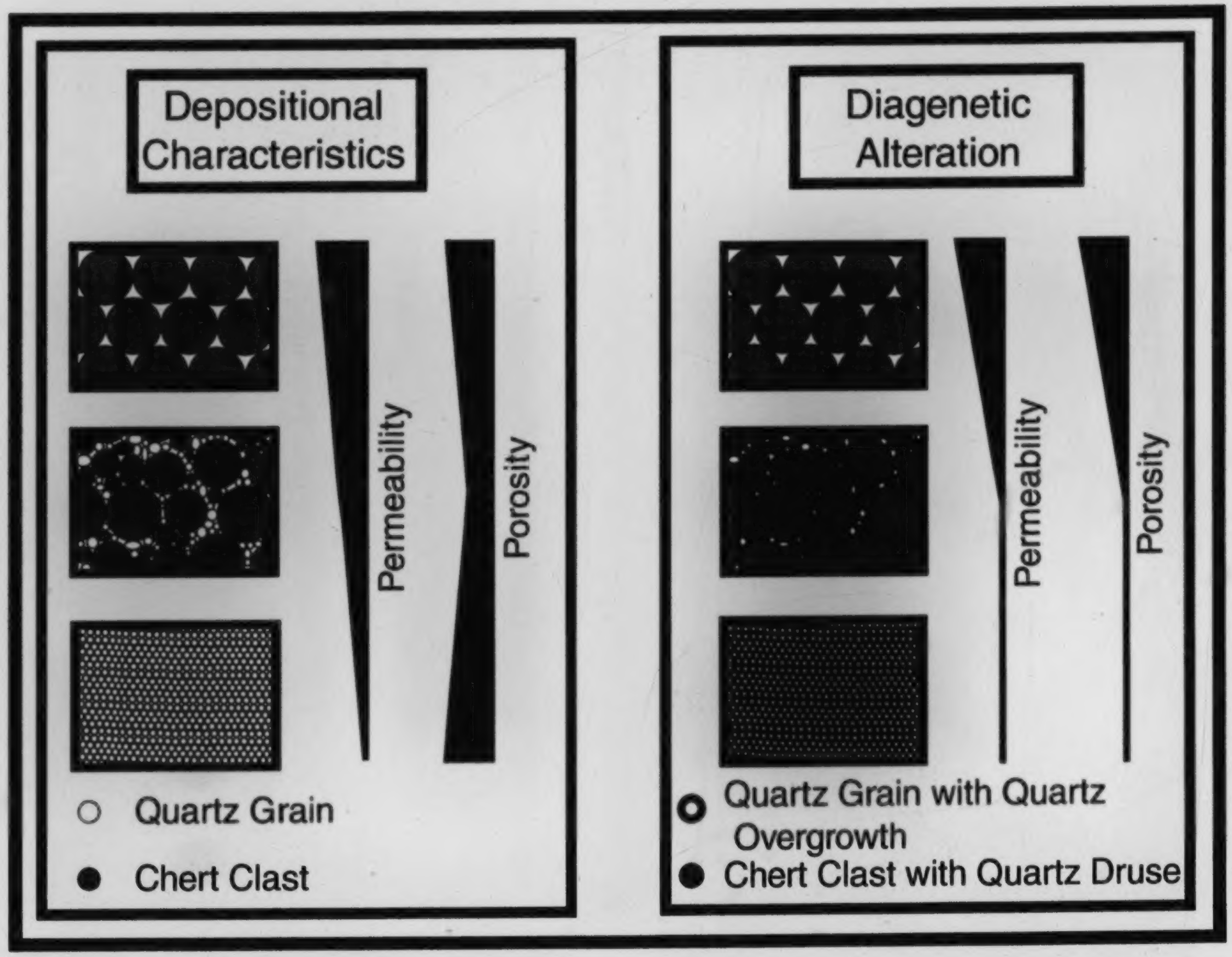
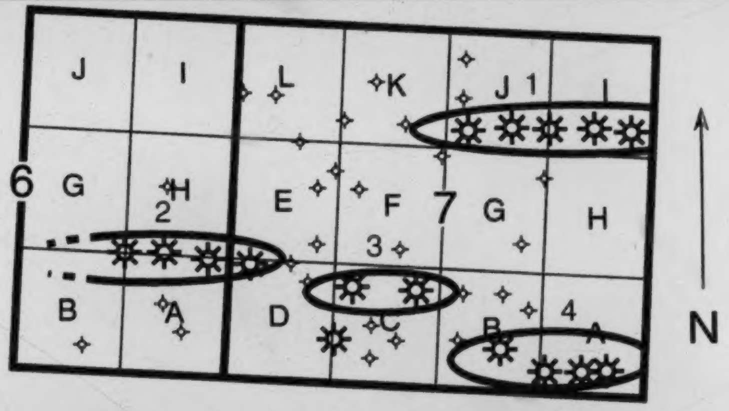
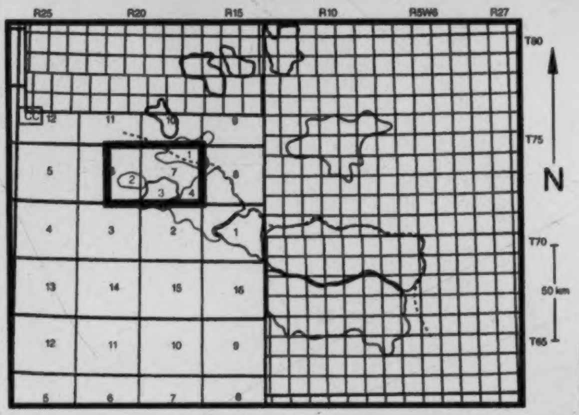

Depositional Characteristics
Permeability
Porosity
○ Quartz Grain
● Chert Clast
Diagenetic Alteration
Permeability
Porosity
○ Quartz Grain with Quartz Overgrowth
● Chert Clast with Quartz Druse

Figure 1.12 – East-west linear character of Cadotte gas fields. Linear nature is controlled by depositional extent of conglomeratic shorefaces contained within non-reservoir sandstones. Commotion Creek study area is identified on the lower map by a red rectangle containing CC within it.

Subsurface Shoreline Orientations in 93-P, NE B.C.


J
I
L
K
J 1
I
6
G
H
2
E
F
7
G
H
3
B
A
D
C
B
4
A
N

⬭ Outline of gas pool controlled by strike of conglomeratic shoreline trend


R25
R20
R15
R10
R5W6
R27
T80
T75
T70
T65
50 km
N
1
2
3
4

Gas Pool Locations:

1. Sundown Field
2. Moose Field
3. Jackpine Field
4. Noel Field

▭ Area enlarged above

Figure 1.13 – Coastal onlap cure and eustatic sea-level fluctuations during the lower Cretaceous Zuni Megacycle (modified from Haq et al., 1988). Cadotte age determination from Yanagi et al. (1988).

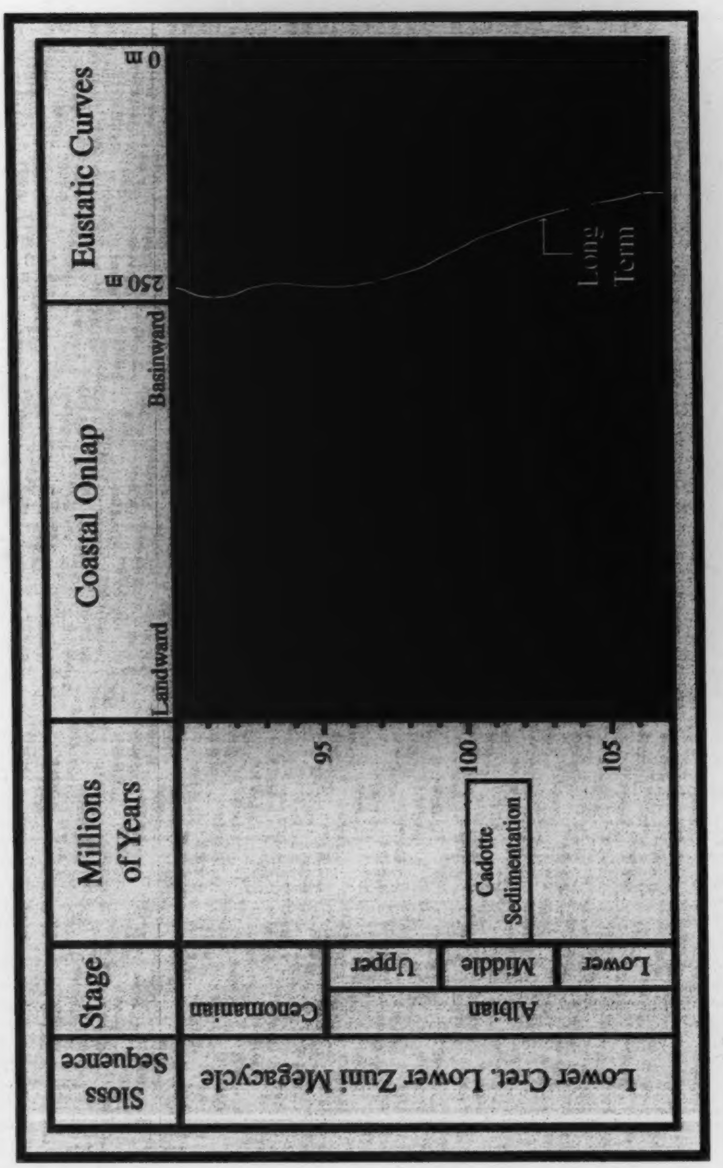

Sloss Sequence
Stage
Millions of Years
Coastal Onlap
Eustatic Curves
Landward
Basinward
250 m
0 m
Long Term
95
100
105
Cadotte Sedimentation
Lower Cret. Lower Zuni Megacycle
Albian
Cenomanian
Upper
Middle
Lower

Figure 1.14 –Lower Albian sea with respect to Mid Albian paleo-pole location. Hurricanes are dominant in Gulfian sea while winter storms dominate in the northern Boreal sea (Diagram courtesy of T.A. Saunders; predicted after Williams and Stelck (1975)). Red rectangle denotes approximate location of study area.

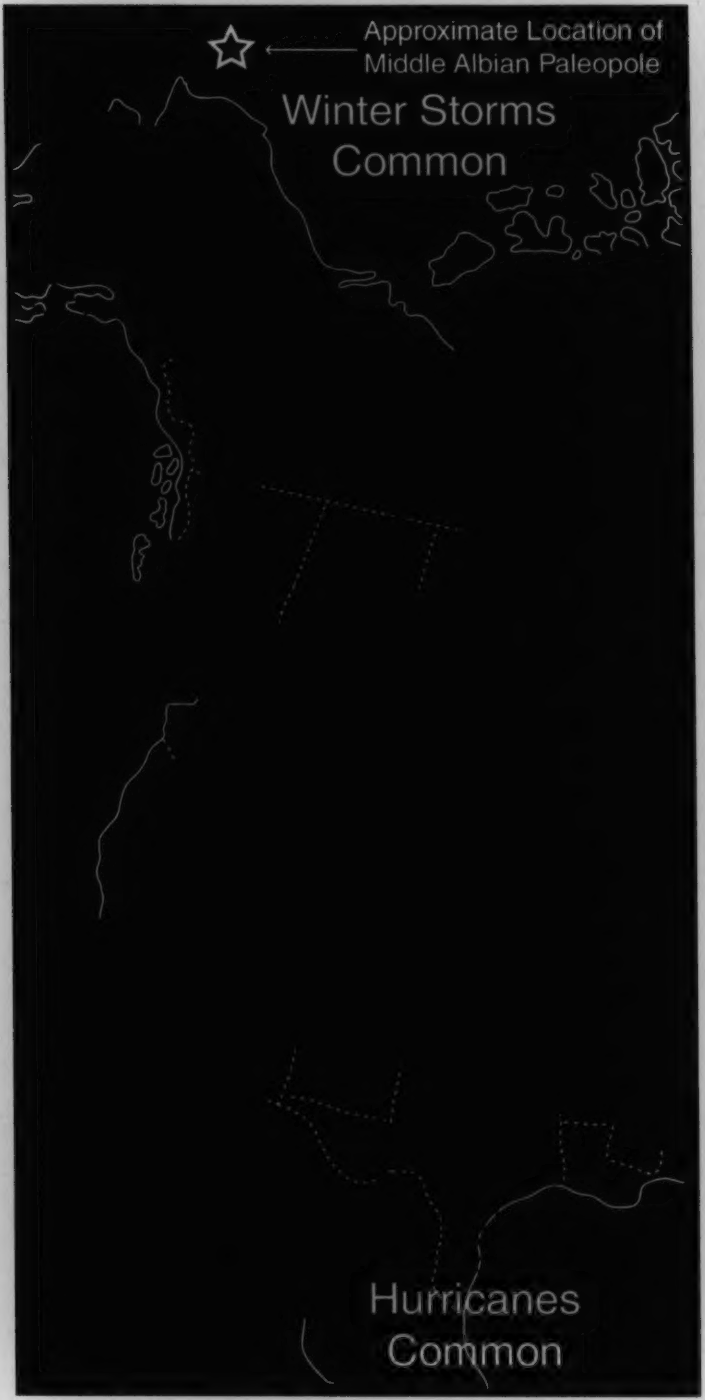

Approximate Location of
Middle Albian Paleopole
Winter Storms
Common
Hurricanes
Common

Figure 1.15 – Paleogeography during the middle Albian, as well as modern preserved sediment distribution. Note the overall northward migration of coastline and associated deposits (yellow), as well as the shaleout at southern margin of the Dawson Creek Graben Complex and basement axis of Peace River Embayment. Present and past deformation front shown as dashed lines and maximum incursion of Albian sea. Diagram constructed from Stott (1983), O'Connell et al. (1990) and Smith (1994).

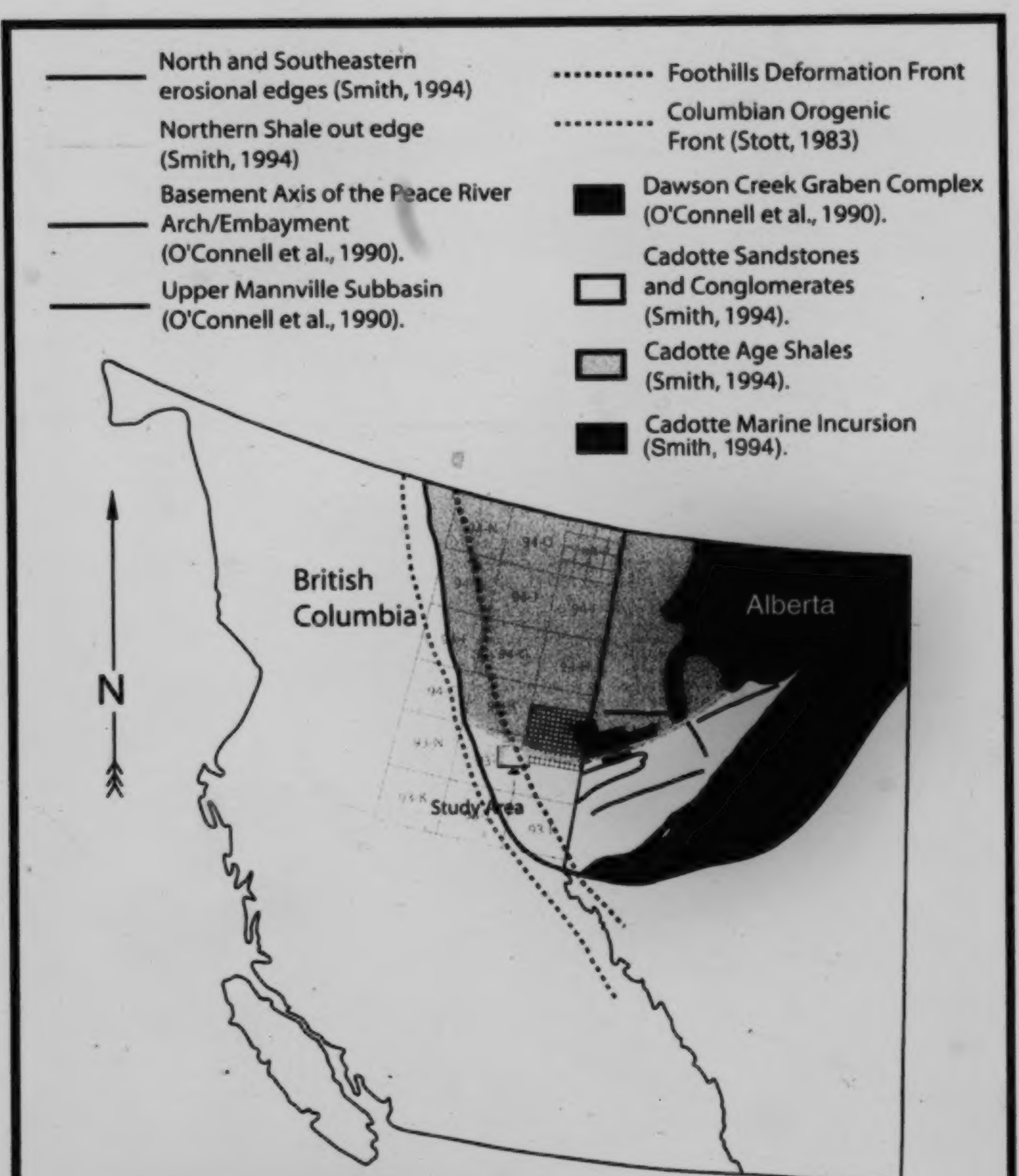

North and Southeastern erosional edges (Smith, 1994)
Northern Shale out edge (Smith, 1994)
Basement Axis of the Peace River Arch/Embayment (O'Connell et al., 1990).
Upper Mannville Subbasin (O'Connell et al., 1990).
Foothills Deformation Front
Columbian Orogenic Front (Stott, 1983)
Dawson Creek Graben Complex (O'Connell et al., 1990).
Cadotte Sandstones and Conglomerates (Smith, 1994).
Cadotte Age Shales (Smith, 1994).
Cadotte Marine Incursion (Smith, 1994).
N
British Columbia
Alberta
Study Area
0
Miles
500
0
Kilometers
500

Figure 1.16 – Distribution of structural belts in Western Canada (from Ricketts, 1989). Red rectangle denotes approximate location of study area. Scale is in kilometers.

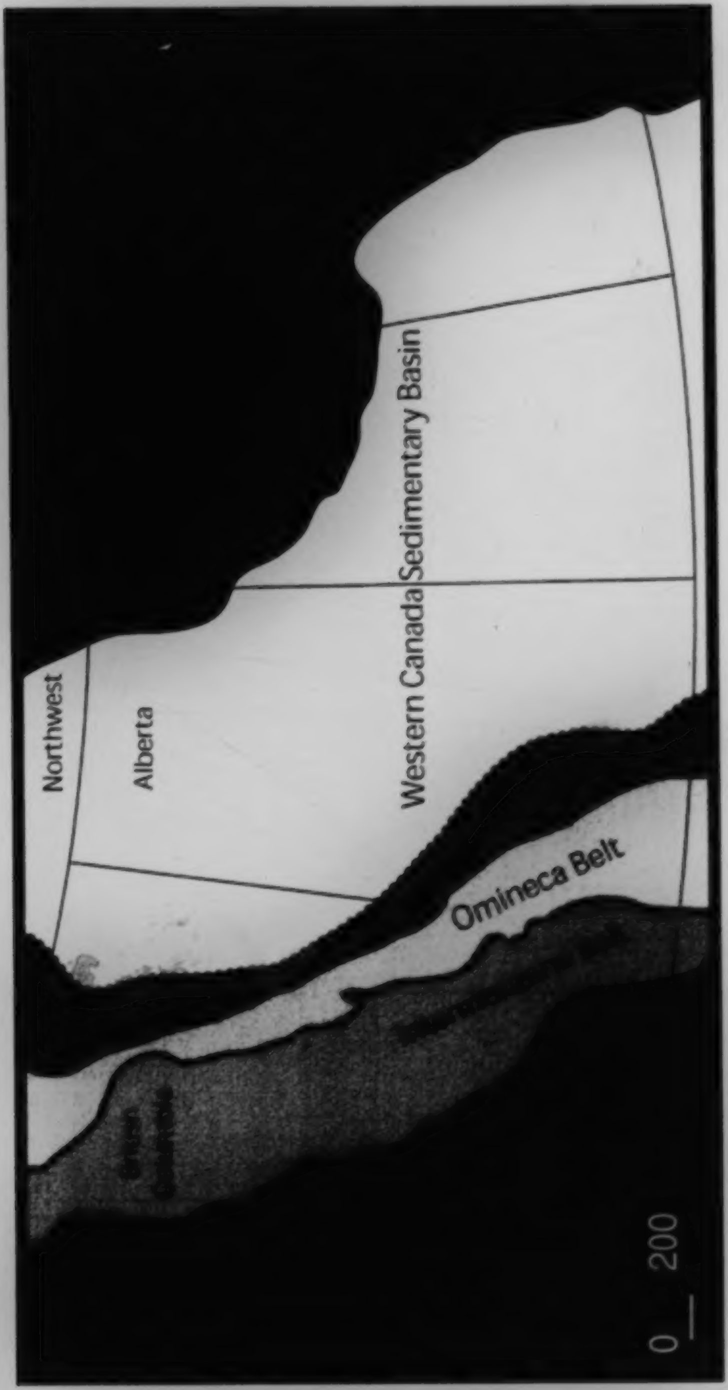

Northwest
Alberta
Western Canada Sedimentary Basin
Omineca Belt
0
200

Figure 1.17 – Regional Cadotte paleogeography illustrating distribution of Cadotte age sediments, main shoreline regression direction, and a trace of the southern margin of the Dawson Creek Graben complex. Major gas fields outlined in red and green, Cadotte incised valley in dark blue and study area location in light blue. Note the arcuate orientation of shoreline strike from west to east. Diagram modified from Smith et al. (1984) and Hayes (1988).

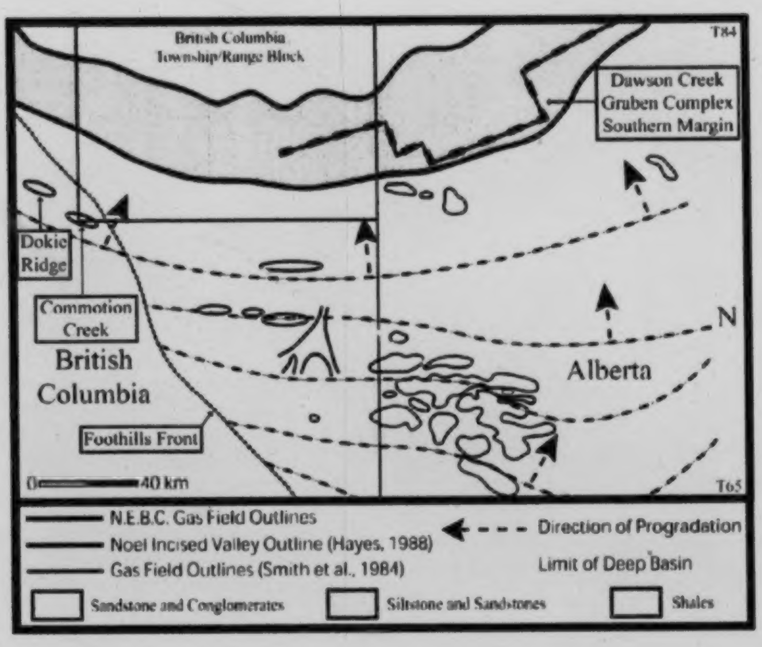
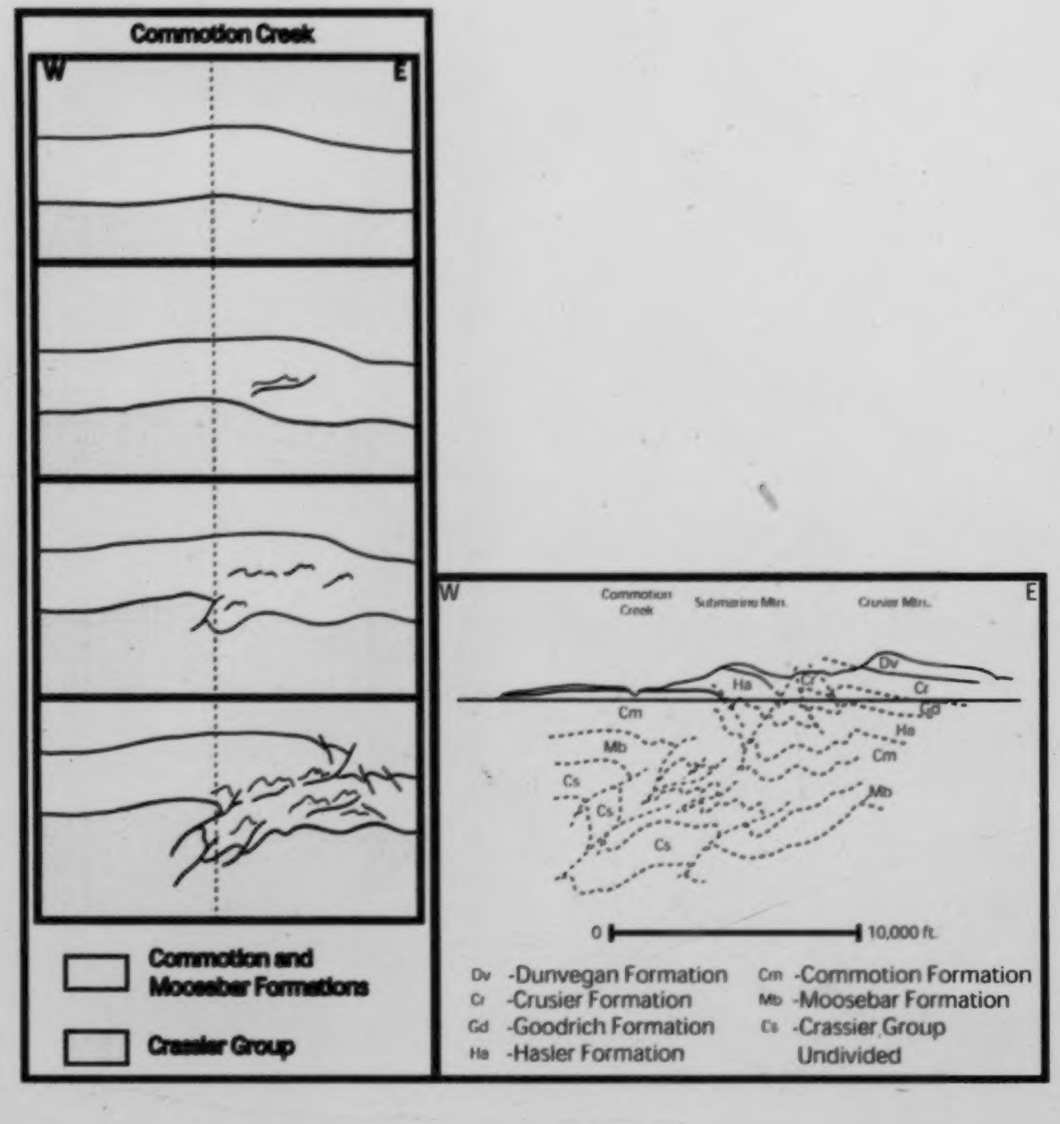

British Columbia
Township/Range Block
T84
Dawson Creek
Graben Complex
Southern Margin
Dokie
Ridge
Commotion
Creek
British
Columbia
N
Alberta
Foothills Front
0
40 km
T65
N.E.B.C. Gas Field Outlines
Noel Incised Valley Outline (Hayes, 1988)
Gas Field Outlines (Smith et al., 1984)
Direction of Progradation
Limit of Deep Basin
Sandstone and Conglomerates
Siltstone and Sandstones
Shales

Figure 1.18 – Structural evolution of the Commotion Creek anticline. Rollover anticline development was controlled by the migration of small westward-dipping thrust faults. The Cadotte Member is included within the Commotion Formation. Commotion Creek location on the fold is depicted by red dashed line in reader's left hand figure. In right figure, black dashed lines indicate stratigraphic contacts while dashed red lines indicate faults. Figure modified from (Hughes, 1967). Note stratigraphic nomenclature is outdated as the name Crassier Group is no longer in use, but instead is interpreted as being equivalent to the Cadomin and Gething Formations (Stelck personal communication).


Commotion Creek
W
E
Commotion and Moosebar Formations
Crassier Group
W
Commotion Creek
Submarine Mtn.
Crusier Mtn.
E
Dv
Cr
Ha
Cr
Cm
Gd
Ha
Cm
Mb
Cs
Mb
Cs
Cs
0
10,000 ft.
Dv -Dunvegan Formation
Cr -Crusier Formation
Gd -Goodrich Formation
Ha -Hasler Formation
Cm -Commotion Formation
Mb -Moosebar Formation
Cs -Crassier Group Undivided

CHAPTER 2 -FACIES DESCRIPTIONS

Sedimentary rocks outcropping at both the Commotion Creek and Dokie Ridge study areas encompass a wide range of lithologies. These lithologic variations each contain characteristic sedimentary and biogenic structures allowing for the delineation of a distinct Cadotte facies succession. Identification and interpretation of individual Cadotte facies provides understanding of the dominant processes that controlled sediment emplacement and evolution, and when integrated with other facies, provides the basis for interpreting depositional environments and potential reservoir quality.

There are three facies associations observed within this study (Table 2.1). These are each composed of individual facies which are "genetically related to each other and have environmental significance" (Collinson, 1969).

Facies Association 2 contains facies of the Cadotte Member and will be discussed in detail. The core from Drillhole #1 (Figure 2.1), provided a clean and complete example of the bulk of Facies Association 2, and was used extensively for detailed lithologic descriptions, as well as the development of a distinct Cadotte Facies succession (Table 2.2).

Facies Associations 1 and 3, contain rocks of the underlying Gates Formation, and the overlying Walton Creek Member respectively, and are discussed in less detail below. The Cadotte facies succession, as well as the underlying and overlying Facies Associations 1 and 3, developed for both the Commotion Creek and Dokie Ridge study areas is outlined and discussed below starting from the stratigraphically oldest (basal) unit and continuing up section.

2.1 Transgressed Shoreface Facies Association 1 - The Gates Interval

Facies Association 1 (FA 1) outcrops at Dokie Ridge. It is preserved as a prominent sandstone feature along the western margin of the main conglomeratic ridge. The sandstones approach 17 m in stratigraphic thickness, and are prominent for about ¼ of the total ridge length (Figure 1.4). This unit represents the uppermost portion of the upper Gates Formation (Table 1.1).

2.1.1 Facies Association 1 – Observations

This interval is composed of flaggy to blocky-bedded, well-laminated, very fine to medium grained, quartz-dominated sandstones, which continually coarsen from the base of the unit to its top. The dominant sedimentary structures in the very fine sandstones include low angle cross stratification, scour and drape surfaces and a hummock and swale appearance. The hummocks are common in the lower portion of the outcrop interval and gradually disappear towards the top of the section as the swaley (scour and fill) structures become dominant. The swales are characterized by, broad low angle, concave up scours that appear to repeatedly truncate one another both laterally and vertically. The individual thicknesses of these hummocky (HCS) and swaley (SCS) cross stratified sand intervals were difficult to determine due to the extremely gradual transition from one to the other, however approximate thicknesses of 10 and 6.5 meters were ascertained.

Anywhere from 1 to 5 gravel interbeds are dispersed throughout the hummocky and swaley cross stratified sandstones. Where present, the gravel beds have sharp, scoured bases and abrupt tops (Figure 2.2) dominated by moderately well sorted, bi- to polymodal, clast supported, small pebble conglomerate. These laterally continuous beds are of variable thickness (Figure 2.2). This coarse grain size is not common within the upper Gates interval. The individual beds range in thickness from 5 cm to almost a meter.

Above SCS beds are the final pervasive sedimentary structures in the upper Gates interval; erosionally bound, burowed, high angle to angle of repose, tabular-like medium-grained quartzose sandstone beds. This cross-bedding is confined to a zone that laterally pinches and swells between 5 and 35 cm. Accurate orientations of individual cross beds could not be measured due to solely 2-dimension bedform preservation. The high angle

TCS beds are also extensively riddled with dark mafic sand-lined, 2-3 mm in diameter burrows (Figure 2.3-C).

2.1.2 Facies Association 1 – Interpretations

Hummock structures similar to those present in Facies Association 1 have been described from lower to middle shoreface deposits of Western Canada's Upper Cretaceous Chungo and Cardium Formations (Duke 1985; Wright and Walker, 1981; Cheel and Leckie, 1992). HCS bedding has a formation attributed to storm enhanced wave energy/orbitals (Harms et al., 1975; Duke, 1985).

Up-section, hummocks disappear, and the presence of pervasive swaley structures takes over. These bedforms match Leckie's (1982) description of swaley cross stratification from the Lower Cretaceous Gates interval of Mt. Spieker and Bullmoose Mountain. At these localities he defines SCS as being characterized by shallow, broad, concave-up scours, filled with low angle laminated (<10 degree) fine-grained sandstones. Leckie (1982) postulates that their formation can be attributed to storm enhanced waves traveling into progressively shallower water depths (where the generation/preservation potential of convex up hummocky bedforms is diminished).

Caddel (2000) has attributed gravel accumulations occurring in the Falher C Member of the Spirit River Formation to storm enhanced, ebb-oriented unidirectional flows returning laden with coarse sediment, from a more landward setting. In this thesis the presence of coarse-grained gravel interbeds within storm deposited sandstones has also been ascribed to the impact of storm energy. The scoured lower, and sharp upper, bed boundaries support a rapid, weakly erosive, event style of deposition. The coarse grain size associated with the interbeds (and its scarcity throughout the bulk of the unit), coupled with the episodic style of deposition, suggests that sediment was transported from a foreign location (and doesn't represent *in situ* reworking of ambient background very-fine to fine-grained sands).

Observations of the high angle cross-stratified bedforms are consistent with descriptions of trough cross stratification (Harms et al., 1975; Harms, 1979). Trough cross stratification (TCS) is common in numerous environmental settings characterized by unidirectional flows. Walker and Plint (1992) and Pemberton et al. (2001) note the common occurrence of TCS in upper shoreface deposits (lying conformably above lower shoreface HCS) common to preserved ancient sand-dominated shoreface sequences distributed throughout the Western Canadian Sedimentary Basin. Arnott (1993) attributes the formation of upper shoreface TCS to be the "result of shear stress asymmetry at the bed related to shoaling surface gravity waves." The medium-grained, quartzose trough cross-stratified beds at Dokie Ridge, lying sharply above very-fine to fine-grained HCS and SCS sandstones, are interpreted to have been deposited in a sand dominated middle to upper shoreface setting (Pemberton et al., 2001).

In Jurassic and Pleistocene intertidal deposits on the United States west coast, Clifton and Thompson (1978) observed a unique trace, which they named *Macaronichnus segregatis*. It was characterized by heavy mineral or mica flake lined trails, which are dominantly horizontal, do not branch and exhibit intense colonization. Clifton and Thompson (1978) postulated that the traces were produced by an organism similar to the modern marine polycheate *Ophelia limacine*. Saunders (1989) also reported what he interpreted to be a modern analog for *Macaronichnus segregatis* contained within intertidal sands of the west coast of Vancouver Island. These traces were produced by the blood worm, *Euzonus mucronata (*also an *Opheliid polychaete)*, and were used to discuss the environmental significance of *Macaronichnus segregatis* contained within upper Cretaceous sandstones of the Bearpaw-Horseshoe canyon Formations outcropping in southern Alberta (Saunders, 1989). Finally, in Alberta's Deep Basin Wapiti gas field, Schmidt (2002) has reported these traces in proximal upper shoreface to foreshore deposits of upper portions of the Notikewin Member (Upper Gates subsurface equivalent).

The presence of *Macaronichnus* and its zone of colonization is controlled by intertidal pumping of oxygen-rich seawater vertically down through high permeability foreshore and upper shoreface sediments (Pemberton et al., 2001). Upper shoreface and foreshore locations are not the only settings prone to the conditions required for colonization by *Macaronichnus* (highly permeable sediments associated with high wave energy conditions). Therefore it may be imprudent to assume that the *Macaronichnus* colonization in the upper Gates TCS unit is directly associated with the emplacement and development of the trough cross beds themselves.

The upwards, increase in grain size, change of sedimentary structures from HCS to SCS to TCS, and presence of coarse grained event deposits, support an interpretation of a prograding, storm dominated lower to upper shoreface succession for the upper Gates Formation outcropping at the base of the stratigraphic section at Dokie Ridge.

Of significant note is the relatively small stratigraphic thickness of the TCS bedding as well as the absence of any planar bedding, the next logical bedding style to be expected in a normally prograding shoreface succession (Walker and Plint, 1992). These observations, coupled with the presence of *Macaronichnus* (and hence high wave energy settings), indicate erosional removal prior to, or associated with, the deposition of the overlying sediments.

2.2 Facies Association 1 – Facies Association 2 Transition

2.2.1 FA1 – FA2 Transition Observations

The *Macaronichnus* TCS unit of the Upper Gates interval is erosionally truncated above by multiple, laterally amalgamated scour surfaces. The scours are marked by the presence of a poorly sorted, very coarse, chert-litharenite to small chert-pebble, matrix supported conglomerate. The conglomerate is gradationally overlain by a moderately sorted, fining-upward, tabular bedded (dips between 10-20°), pebbly coarse to very coarse chert-rich sublitharenite sandstone bed (Figures 2.3 and 2.4). Together these two lithologies exhibit moderately dipping, sharp based, normally graded beds that can be interpreted as trough cross stratification, with the basal conglomerate simply representing the amalgamation of the more coarse toe sets of the tabular sublitharenite bedform foresets. The basal scour surfaces of many of these TCS beds contain scattered coalified wood fragments with dominant long-axis orientation azimuths of 56/236 degrees (NE/SW).

These sandy to pebbly, TCS beds are abruptly overlain by well-sorted, uni to bimodal, granular to pebbly, stratified conglomerates (Figures 2.3 and 2.4). Subaqueous gravel dunes are very well preserved and are symmetrical with linear, well-developed rounded crests. Dunes are up to 20 cm in height (from trough to crest) and have a wavelength of up to 2 meters, with dune foreset slopes of approximately 10°.

2.2.2 FA1 – FA2 Interpretations

The source of the sediment composing the TCS beds is attributed to erosional removal and reworking of underlying shoreface sediments. The coarse nature of the trough cross beds, coupled with the conglomerate event deposits present in the HCS and SCS portions of the Upper Gates interval, may be indicative of a pre-existing /pre-reworked coarse-grained gravel-rich proximal upper shoreface to foreshore. If this, in fact, is the case then the presence of unidirectional current-generated bedforms suggests that the emplacement and formation of this unit may be attributed to erosional removal and subsequent wave reworking associated with a deepening.

A deepening would effectively expose previous shoreface deposits to high levels of wave energy associated with the passage of upper flow regime sheet, and asymmetric oscillatory, flows. Encroaching wave processes would remove previously deposited sediment and transport it into either deeper water or further landward (as *Macaronichnus* colonize below the sediment water interface). The process of erosion would continue until either an equilibrium profile is formed or the area is flooded beyond the influence of wave energy.

Ever increasing water depths also expose existing deposits to both continually decreasing wave energy, and asymmetry. The symmetrical nature of the gravel bedforms coupled with the high degree of sediment sorting/winnowing, indicates sediment transport/reworking and deposition by highly symmetric oscillatory flows.

The transition in wave energy evident in the upper Gates/ Facies Association 2 transition is observable as a shift in dominant sedimentary processes from erosion, to asymmetrical bedform migration and finally winnowing during the generation of symmetrical dunes. It is interpreted that this transition in wave regime strength is attributable to a shoreline in a state of transgression/flooding. Leckie (1988) has reported the common association of similar coarse-grained symmetrical bedforms, which he named coarse-grained ripples, coexisting with numerous transgressive surfaces, bounding stratigraphic intervals throughout the Western Canadian Sedimentary Basin. Posamentier and Allen (1999) also note the common association of a ravinement deposit (winnowed transgressive lag) capping transgression related surfaces of erosion.

2.3 Prograding Offshore Transition to Shoreface Facies Association 2 – The Hulcross and Cadotte Intervals

Facies Association 2 (FA 2) represents an accumulation of shales, siltstones, sandstones and conglomerates. In outcrop, not all of the facies are exposed at both study areas; however, when rocks of the same facies do outcrop at both localities, they exhibit similar weathering characteristics. The coarsest chert-rich conglomerates and sandstones develop the steepest cliff faces (Commotion Creek) or the most prominent ridges (Dokie Ridge). These rock units also develop the most intense (black) lichen coverings and (tan) carbonate crusts. Finer grained quartzose sandstones are somewhat more recessive, yet are still persistent enough to remain exposed. At both localities, the higher the shale and siltstone content of a given unit, the greater the susceptibility to erosion and ground covering (Figure 2.5).

The second Facies Association consists of 7 individual facies, coupled with a few key facies transitions. The facies observations and interpretations are laid out below. A Facies Model detailing the interpretation of Facies Association 1, as well as the generalities of its stratigraphic relationships with the underlying Gates and overlying Facies Association 3, will be discussed in the following chapter.

A few final comments should be made in regards to the facies model discussed below. As the name of the section indicates, Facies Association 2 has been interpreted as a prograding offshore transition to shoreface succession. The reader will notice, however, that the shoreface model discussed below differs significantly from the more conventional model applied to Facies Association 1 above. The principle difference lies with both the thickness of the fine-grained sandstone to conglomerate intervals, as well as the dominant grain size of distinct morphodynamic settings within the 2 models. FA 2 has a much coarser maximum grain size, and contains a significantly larger volume of sand and gravel in depositional settings, which are dominated by mixed sands, silts and muds in FA 1. For these reasons it is the authors bias that although FA 2 is interpreted using shoreface terminology, it may in fact, also have a less obvious deltaic influence. As no distinct associated Cadotte fluvial systems were found in close proximity to the study area, the author feels more comfortable describing the unit using descriptive terminology associated with the dominant observed, and interpreted, sedimentary processes (wave system). This semantic issue may be simplified by suggesting a potential link between the dominant process of coastal sediment wave reworking (during both fairweather and storm conditions), and increased volumes of sand and gravel derived from either a nearby sediment source (active delta), or a recently abandoned one (wave reworked delta).

2.3.1 Distal Ramp, Facies A Observations

Facies A is only exposed at the surface along Dokie Ridge. It outcrops as a thin (<50 cm thick) laminated siltstone (Figure 2.5) bed lying abruptly above a thin conglomeratic dune bedform of the upper Gates. Undoubtedly a thicker accumulation of Facies A is present beneath much of the surface ground cover, but the consistent, recessive nature of this facies makes observation and analysis extremely difficult and therefore not much can be said regarding its characteristics.

The presence of prominent sand dominated outcrops immediately overlying and underlying this facies infer that Facies A is somewhat lithologically consistent for much of the covered section between the prominent sandstones (Figure 1.4), and thus an approximate interval thickness of 14 m is estimated. The transition between Facies A and overlying Facies B is only partially exposed, but the presence of similar, yet continuously thinning, recessive intervals, interbedded with continually thickening, stratigraphically discontinuous prominent sandstones beds present within Facies B indicates a normal, gradational facies transition. This transition has been placed at the base of the first occurrence of a prominent, vertically discontinuous sandstone bed.

2.3.2 Distal Ramp, Facies A Interpretations

Due to the recessive nature of this interval no definitive interpretations can be provided, however a few comments may be made. First, the continuous, recessive nature of the interval, located between prominent sandstone and conglomerate outcrops, suggests that the lithology of the interval is of a less resistant nature, probably siltstone and/or shale. The lack of any intervening prominent sandstone outcrops suggests that this interval is of a somewhat consistent lithology throughout its entire vertical extent, and is therefore somewhat environmentally isolated with respect to sand and gravel deposition.

Second, the stratigraphic position of this facies, lying directly above an erosive contact (separating it from underlying lower shoreface deposits) represents a transition from higher to lower energy and has been interpreted as representing a deepening event (discussed previously). The gradational upper facies transition represents a minor decrease in water depth (a minor shallowing) evidenced by the gradual appearance of thin, sheet to oscillatory flow deposited sandstone beds (Facies B - see below). This shallowing is reflected in the sedimentary record as a change in genetically related sub-environments from a mud and silt dominated distal ramp to a mixed sand, silt and mud outer offshore transition. Given the fine-grained recessive nature of this deposit, and its stratigraphic position, it has been interpreted as the basal Hulcross Formation.

2.3.3 Mixed Outer Offshore Transition, Facies B Observations

Facies B is present at both Commotion Creek and Dokie Ridge. Exposure is much better at Commotion Creek due to the vertical nature of the outcrops; therefore the discussion will be based dominantly on this study area. Within the Commotion Creek study area this facies is only present at a single section location, lower Commotion East - CE-1Lower (Figure 1.5).

This facies consists of interbedded sandstones, siltstones and shales (Figure 2.6) and exhibits the greatest range and variability of sedimentary and biogenic structures (compared with other Cadotte facies). No lower facies boundary is exposed at either location. The thickness of a possibly equivalent (yet recessive and dominantly covered) interval at Dokie Ridge is approximately 30 to 35 m thick; however, due to the covered nature of the Dokie Ridge outcrop, an accurate thickness is difficult to attain. A basal transition was assigned, somewhat speculatively, at the occurrence of the first prominent sand outcrop lying approximately 14 m above the base of underlying Facies A.

The lower portion of the Commotion East section appears to contain approximately 50% siltstones and shales, and 50% sandstones (Figure 2.6). As the top of the section is approached the percentage of shale appears to decrease and is replaced by either siltstones or progressively thickening sandstone beds. This vertical lithologic transition is also accompanied by an apparent ichnologic transition from more small scale burrows being dominant near the base of the section to more robust, well developed forms dominating near the section's top. The extremely recessive and fractured nature of the shales inhibits the confident recognition of most primary trace fossils or sedimentary structures, however occasional *Thalassinoides* are preserved on the soles of an overlying sandstone or siltstone bed (Figure 2.7-D). Laterally continuous sideritized horizons are common. This sideritization consists dominantly of a series of laterally adjacent diagenetic siderite concretions (showing well-defined elliptical growth rings). To a lesser degree, occasional siderite pebble and cobble horizons are encountered mantling the base of low angle laminated sandstone beds (Figures 2.8-A&C).

Siltstones commonly contain appreciable amounts of sand and can therefore more accurately be classified as sandy-siltstones and silty-sandstones. These beds most commonly directly overly, or are interbedded with, sandstone beds. No primary lamination or sedimentary structures are visible, but the common abundance of biogenic structures often gives these beds a chaotic appearance and it is not uncommon for the entire bed to be completely bioturbated by *Phycosiphon* and/or *Chondrites* (Figure 2.9-B). Scoured upper bedding surfaces are common, and when present, are overlain by either parallel, low angle, or ripple laminated sandstone beds (Figures 2.10).

Sandstone beds thicken upwards, range in thickness between 10 and 100 cm, and are commonly characterized by either; parallel (Figure 2.10-A), low angle (Figure 2.10-B), or low amplitude, symmetrical ripple laminations (Figure 2.10-C) - all of which may contain diagenetic pyrite (Figure 2.8-B).

Parallel laminated sand beds often exhibit normal grading from upper very fine-grained sandstone through siltstone to capping shales and average between 5 and 15 cm in thickness. They have a sharp basal surface, which may locally contain flute casts (Figure 2.11-B), siderite pebbles (Figure 2.8-A) or wood debris (Figure 2.12-A). Much of the wood debris is either coalified or flattened due to compaction, but where present may show evidence of biologic colonization supported by the presence of club shape, sand filled borings (Figure 2.12-B). One continuous 2 to 5 cm thick laterally continuous coal seam is present but is anomalous with respect to the remainder of the stratigraphic interval (Figure 2.8-D).

Low angle laminated sand beds are dominated by upper very fine-grained sandstone, and tend to exhibit a distinctive flaggy weathering profile (Figure 2.13-A). Lamination dip angles range between 0 and 10° with dip values decreasing towards the top of each individual bedform (Figure 2.10-B). The beds have sharp basal surfaces which may be characterized by siderite pebbles, thin (<20cm) accumulations of coarse sandstone, flute and load casts, and/or wood debris. Bed amalgamation is common towards the top of the section. The amalgamated beds occasionally contain soft sediment deformation dominated by flame structures and/or soft sediment folds (Figure 2.11-A&C). The soft sediment folded beds are frequently scoured at their upper boundary by an overlying undeformed low angle laminated sandstone bed (Figure 2.11-C). Less commonly, the distorted beds form mounded sand accumulations (Figure 2.6-B). Low angle laminations may also be locally disrupted, though not to the point of non-recognition, by the presence of *Planolites*, *Schaubcylindrichnus*, *Paleophycus*, *Diplocraterion*, *Skolithos* or escape traces (Figures 2.9-A & 2.14). Occasionally (at Dokie Ridge) some of the low angle laminations show lag concentrations of ripped up, transported mud walled *Rosellia* (Figure 2.15-B)

Low amplitude, straight crested, symmetrical ripples may exist on their own, or cap the tops of random low angle laminated beds. They're commonly exposed on bedding surfaces and are characterized by peaked, continuous, weakly bifurcating, parallel crests, with broad, shallow troughs (Figure 2.13-B&C). Ripples have an approximate wavelength of 10 to 15 cm and a trough to crest height of 1 to 3 cm. These ripple beds are weakly aggradational and often show foreset laminations oriented in opposite directions (Figure 2.10-C). The sediment itself is almost devoid of trace fossils, with the occasional presence of *Chondrites* being the exception (Figure 2.7-A). Where the upper bedding surface of rippled beds is exposed (on talus debris) it may be marked by the presence of *Gyrocorte* and/or *Muenstaria*, albeit in limited concentrations (Figure 2.7-B&C).

The ammonite *Pseudopulchellia pattoni* was recovered from a sandstone bed near the base of the Facies B section at Commotion East, and represents the only fossil found during the course of the study (Figure 2.15).

2.3.4 Mixed Outer Offshore Transition, Facies B Interpretations

The presence of interbedded sandstones, siltstones and shales demonstrates the variability in dominant processes controlling the emplacement of Facies B sediments. The required current velocities responsible for depositing mud and silt is much lower than that required transporting sand. Further, the increase in sand content up section also suggests that the vertical section represents the approach of a source of sandy sediment (basinward shift of facies).

The low angle laminated sandstone beds exibit characteristics diagnostic of hummocky cross-stratification as defined by Harms et al., 1975. Since its original definition hummocky cross-stratification (HCS) has been reported from numerous localities both globally and within the Western Canadian Sedimentary Basin (Hunter and Clifton, 1982; Duke, 1985). Historically, its development has been a topic of some debate (Klein and Marsaglia, 1987) heightened by the lack of any modern analogues. The current accepted mode of formation focuses on purely oscillatory, to extremely oscillatory dominated combined flows, associated with large storm wave sets (Harms et al., 1975; Duke et al., 1991). The dependence on storm waves as a controlling mechanism of formation requires that these deposits must form above storm wave base. However, the presence of shaley interbeds indicates that Facies B must also have been deposited within an ambient environment of suspension sedimentation (below fair weather wave base), these two lines of evidence then suggest that the HCS of Facies B was deposited in a dominately low energy setting periodically exposed to high energy storm processes conditions.

Further support for episodic sedimentation by wave processes is provided by the common occurrence of symmetrical wave ripples capping the underlying HCS storm beds, and siderite pebbles, coarse sand, flute casts or wood debris common along the HCS basal bedding surfaces. The occurrence of pebbles, coarse sand, wood debris and flute casts along the basal bed boundary supports a high energy erosive mode of bed emplacement and in essence, is the bed load deposit of a storm. The presence of wave formed ripples at the upper bed boundary represents the waning stages of the storm events, as ever decreasing storm wave energy continues to suspend and saltate the sediment until the storm finally passes (Bourgeois, 1980).

A less common characteristic of the Facies B HCS beds is the presence of soft sediment deformation, dominated by soft sediment folding and flame structures. Both of these examples represent semi-plastic deformation of partially liquified sediment (Boggs, 1995). The presence of underformed units directly above and below the deformed horizons suggests that the agent of deformation was not powerful enough to penetrate beyond the confines of the individual bed and as such, must represent a local control affecting only a thin portion of previously deposited sediments (from the sediment water interface down). As well, the common occurrence of storm deposits (HCS) erosively cutting the upper bed boundary may hint at deformation driven by the impact of storm waves on previous deposits of the ocean floor, precluding the arrival and emplacement of the actual associated storm bed.

The parallel laminated sandstone beds, exhibiting normal grading, sharp bases characterized by flute casts, and the absence of any obvious capping wave ripple laminae support emplacement during upper flow regime sheet flow (Prothero and Schwab, 1996). These beds appear similar to units described from the Jurassic Fernie-Kootenay transition of the Western Canadian Sedimentary Basin interpreted as turbidite return flows driven by increased hydraulic head in coastal settings associated with storm surge in the nearshore zone (Hamblin and Walker, 1979). In essence, the parallel laminated sandstone, like the HCS, represents high-energy (storm) event conditions, in a normally suspension sedimentation setting, simply emplaced by different flow conditions/characteristics.

The presence of preserved trace fossils can be used to aid in, and support, environmental analysis (Pemberton et al., 1992A). Trace fossils, although not direct indicators of water depth, provide the geologist with the potential to gain insight into specific environmental factors characteristic of the depositional setting in which they were formed (Frey et al., 1990). The various trace fossils present in Facies B repetitively and predictably occur only within one of three lithologic units (eg. either sandstones or siltstones and shales), rarely does one type of trace occur in both the sandstones as well as the siltstones and shales. The ichnologic assemblages associated with specific lithologic beds were used to define two distinct trace fossil suites, one for the sandstones and another for the siltstones and shales.

The first suite, occurring only in sandstone beds, consists of a low concentration, low diversity assemblage dominated by (but not restricted to) dwelling forms charaterized by the presence of vertically to sub-vertically oriented *Skolithos*, *Diplocraterion* and *Schaubcylindrichnus*, with appreciable populations of horizontal *Palaeophycus*, and minor occurences of *Planolites*. This assemblage is dominated by traces comprising members of the *Skolithos* ichnofacies which Pemberton et al. (1992B) indicate as representing structures created by suspension feeding organisms. The presence of structures created by the act of suspension feeding requires an environment with sufficiently high enough energy levels so as to be able to entrain and transport food within the water column (Pemberton et al., 1992B), ie. the food is brought to the organism. The low diversity of traces present and the low concentrations of those that are present, indicate an environmentally stressful setting. Howard (1975) cites sedimentation rate as an important stress affecting benthic organisms, stating that the longer the period of bed exposure to low energy conditions, the higher the degree of sediment reworking and disruption by burrowing organisms. Ichnologic support for high rates of sedimentation is provided by the association of fugichnia (escape traces) with many of the low angle laminated sand beds. These escape structures were created by an organism attempting to equilibrate with the sediment water interface following a period of rapid sedimentation. This indicates that many of the sandstone beds would have been deposited in a relatively short period of time (within the life span of the organism responsible for the formation of the structure).

The second suite, present in the siltstone and shale beds, is dominated by horizontal feeding structures characteristic of the *Cruziana* ichnofacies. The traces identified consist of *Phycosiphon, Chondrites, Thalassinoides, Muenstaria, Gyrocorte* and *Planolites*. This assemblage consists of a broader range of taxa than that present in the intervening sandstone beds, as well, slabbed samples of the siltstones appear to show a higher concentration of burrow activity. However the recessive and commonly intensely fractured nature of the siltstones and shales in outcrop inhibits thorough trace fossil recognition and the ability to study burrow concentrations and diversity. The *Cruziana* ichnofacies has been attributed to the behavior of deposit feeding (Pemberton et al. 1992B). Deposit feeding organisms require a sustainable amount of food material to be present within the sediment they colonize. Pemberton et al. (1992A) point out that lower energy conditions are required for food material to settle out of the water column.

The presence of two juxtaposed ichnofacies (*Skolithos* and *Cruziana*), associated with different environmental conditions, is indicative of a depositional setting susceptible to rapid energy fluctuations and variations in hydrodynamic conditions (Pemberton et al., 1992C). This juxtaposition is responsible for the development of a sedimentary fabric termed "Lam-Scram" by Howard (1975), which consists of minor amounts of bioturbation associated with laminated sand beds, interbedded with intensely reworked (scrambled) siltstone and shales beds. Lam-scram textures indicate periods of rapid deposition (faster than rates of biologic colonization) responsible for the deposition and preservation of laminated sand beds that periodically occur in areas characterized by slow, fine grained sedimentation (where biologic colonization normally outpaces sedimentation) (Bourgeois, 1980). Pemberton and Frey (1984) described *Skolithos* and *Cruziana* ichnofacies organised in a similar fashion to that evident in Facies B, from the upper Cretaceous Cardium Formation outcropping at Seebe Dam in west central Alberta. They interpreted the succession as a low energy silty to shaley offshore characterized by the frequent occurrence of high energy sandy storm beds. The *Cruziana* assemblage represents the fairweather, normal background conditions resonsible for the deposition of siltstone and shale, while the *Skolithos* assemblage is more indicative of ecologically stressful sandy events (storms) (Pemberton and MacEachern, 1996). The *Skolithos* ichnofacies associated with the event deposits represent an opportunistic suite that is able to rapidly colonize an environment undergoing, or having just undergone, storm deposition. As the storm event wanes, these organisms die off quickly and are replaced by a fairweather *Cruziana* assemblage associated with normal background conditions (Rhoads, 1975; Pemberton et al., 1992C). The interpretation of storm deposition in a mixed, middle shelf environment for Facies B, derived from ichnologic analysis, agrees very well with conclusions derived by the sedimentologic analysis.

The presence of club shaped borings in wood debris could best be classified as *Teredolites clavatus* as described by Lavigne (1999). However due to their occurrence in what is interpreted as rafted wood, their environmental significance lies only in that they were originally formed in a marine environment.

Sideritized horizons present within this facies appear to have been formed very recently after deposition as they would represent the source for siderite pebbles that mantle the bases of HCS and planar beds (due to the absence of any other siderite sources stratigraphically higher in the section). Stable isotope work carried out by Bloch (1990) on siderite beds of the Harmon Member of the Peace River Formation (age equivalent sedimentary deposits) from the northwest reaches of the Deep Basin indicated mineral formation from fluids with a strong meteoric component, mixing with basinal waters at temperature between 10-25°C. This suggests formation in a basin margin setting. Bloch (1990) also discussed the presence of early diagenetic pyrite and attributed it to bacterial sulfate reduction taking place before siderite formation, in the earliest stages of the diagentic sequence.

The association of sedimentologic and ichnologic attributes of Facies B supports deposition in a mixed, outer offshore transition, and has been interpreted as the upper Hulcross Formation.

2.3.5 Storm Dominated, Sand Rich Inner Offshore Transition, Facies C Observations

Facies C is partially exposed at both the Commotion Creek and Dokie Ridge study areas, although, at neither location is both an upper, and lower, facies boundary evident. Commotion East offers the thickest, and most sedimentologically continuous exposure of this facies (16.25 m), in a small quarry approximately 200-250 m north along the east side of the Walton Creek Forest service road. The lower boundary of the unit is buried beneath surface cover, and therefore, only an inaccurate approximate thickness is possible. At Dokie Ridge this facies is exposed as a moderately prominent, laterally continuous to discontinuous outcrop that periodically protrudes through the surface cover. The discontinuous nature (and ground cover) of the Facies C outcrop at Dokie Ridge also inhibits the ability to obtain an accurate thickness measurement. However, the Dokie Ridge location does offer a more accurate approximation of the unit's thickness than does Commotion Creek, with potential values ranging between 11 and 20 m.

At Commotion West and Commotion Creek the upper 2 to 5 m of this facies is exposed at the base of many of the large cliff faces, or at periodic positions along the creek itself. The dominant lithology is very similar in nature to the HCS sandstones contained within the underlying interbedded sandstones, siltstones and shales of Facies B, and probably represents a similar deposit marked by the elimination of the siltstone and shale interbeds, as well as the absence of the planar and ripple laminated bedding styles. This facies is overwhelmingly dominated by upper very fine-grained quartz cemented sand grains and as such, is classified as a quartzose sandstone. The top 2 to 3 m of the unit, however, does contain minor concentrations of chert granules and lower medium grained quartz to lithic sandstones (discussed below).

Bedding style is dominated by low angle laminations that shallow towards the top of the bed. These laminations define bedforms that appear to consist of 3-dimensional hummocks and swales. The laminations may have scoured tops (base of the overlying swales) followed by subsequent lamination drape/onlap (swale fill and hummock) (Figure 2.16-B&C). The laminations dip at angles ranging between 0-10° and appear to thicken down, and along, the lamination, from the hummocks, into the adjacent swales. As the top of the facies interval is approached, the bedding style appears to become dominated by the swales, with few to no hummocks present. As well, there is a relatively small increases in the percentage of lithic fragments and coarser sand (Figure 2.16-B&C). The stratigraphic location marking the disappearance of hummocks lies approximately 2-3 meters below the Facies C upper contact.

Burrowing is observed by the presence of cryptobioturbation, however, locally, rare *Palaeophycos* and *Skolithos* may disrupt laminations.

Towards the top of the facies, chert-pebble filled gutter casts and coarse sand to gravel defined stringers are occasionally present (Figure 2.16). The gutter casts range in apparent width from 15 to 30 cm, depth of 5 to 10 cm and have wall angles of up to 35 degrees. The structures are filled with a polymodal, poorly sorted accumulation of chert pebbles common to overlying facies. The gutter casts don't appear to show a long axis orientation consistent with either the strike or dip sections. This indicates that they are oriented somewhat oblique to outcrop exposures. The dominance of solely 2-dimensional gutter cast exposure made it extremely difficult to obtain any accurate azimuth measurements, and therefore only approximate orientations could be obtained (dominantly NE-SW).

Pebble to coarse sand stringers are present in the highest concentrations within the upper 2 to 3 m of the facies and are often accompanied by a change in dominant bedforms (the disappearance of hummocks) coupled with a subtle increase in grain size. The grain size is still dominated by upper very fine-grained sand but has incorporated both fine- and medium-grained sand into the matrix. Concurrent with this increase in grain size is an increase in chert and lithic content, however the dominant lithology remains quartz.

2.3.6 Storm Dominated, Sand Rich Inner Offshore Transition, Facies C Interpretations

The low angle laminated sandstone beds that dominate Facies C appear to represent hummocky cross stratification (HCS) as described by Harms et al. (1975). The identical nature of the HCS beds (in both Facies B and C) suggests that deposition of Facies C sandstones was also controlled by episodic storm processes. The principle variation between the two facies lies in the lack of Facies C background sediments preserved in the rock record. This variation suggests that the transition from Facies B to Facies C represents a shallowing of the locus of deposition (basinward shift of facies). This shallowing represents a shift in energy regimes from lower (Facies B) to higher (Facies C), and concordantly a shift in environment of deposition from a mixed, storm influenced, outer (Facies B) to sand-rich, storm dominated inner offshore transition (Facies C).

The amalgamation of HCS beds indicates that the frequency and magnitude of storm event sedimentation effectively removed all evidence of fair-weather suspension sedimentation. This period of early storm erosion is followed by waning-stage storm deposition (deposition by continually decreasing storm currents). Due to the event style controls of Facies C deposition, it is assumed that dominantly, deposits associated with the highest magnitude storms stand the best chance of preservation in the rock record. The bedding style transition from HCS to SCS is indicative of HCS processes occurring in shallower water regions (Leckie and Walker, 1982). In other words, SCS is a shallow water equivalent of HCS, and in this occurrence, is interpreted to be roughly equivalent to fairweather wave base.

The presence of cryptobioturbation supports deposition in a marine environment (Pemberton et al., 2001). Pemberton et al. (2001) describe cryptobioturbation as being meiofaunally reworked sediment exhibiting minimal disruption to the primary sedimentary fabric of the host deposit. Meiofauna, organisms between 0.1 and 1mm in size, are small enough to swim between the grains of sediment, leaving only a "fuzzy" appearance as evidence of their passing (Pemberton et al., 2001).

Skolithos and *Palaeophycus*, both of the *Skolithos* ichnofacies, are commonly associated with high-energy nearshore systems (Pemberton, 2001). The low abundance of the two species in Facies C is common in regions of high sedimentation rate, where sediment is deposited at a rate exceeding that of biologic colonization. Howard (1975) notes that when an event bed reaches a critical thickness (about 30 cm – of which most of the Facies C beds are) the chance of biogenic reworking drops off significantly, and is commonly restricted to only the upper few centimeters of the bed. The uppermost few centimeters of many of the Facies C HCS beds have been erosionally removed during the emplacement of the overlying bed. In essence, storm processes don't only create a scenario favored for colonization by members of the *Skolithos* ichnofacies, but they also effectively remove most of the evidence of their presence (due to high substrate mobilization during storms)(Pemberton and MacEachern, 1996).

Gutter casts and pebble/coarse-sand stringers represent evidence for the transport of sediment from overlying coarse grained facies into a region dominated by very fine grained sand. They also help establish an important sedimentologic link between Facies C and overlying Facies D.

Gutter casts are common in offshore transition to shoreface settings (Chiocci and Clifton, 1991). They've been described in mud, silt and sand, have exhibited numerous types of fill and possess cut and fill events associated with both significant, and insignificant, amounts of time (Goldring and Aigner, 1982). The polymodal, poorly sorted nature of the Facies C gutter cast fill is indicative of rapid sedimentation, and supports a depositional link with the creation of its associated scour (eg.

sedimentologically related, and temporally insignificant cut and fill). The fill was transported by grain saltation as the traction component of offshore oriented, scouring, unidirectional currents. These currents represent the distal terminations of seaward oriented, storm return flows. Storm generated currents are commonly associated with gutter cast formation (Leithold and Bourgeois, 1984; Leckie and Krystinik, 1989). The specific type of storm return flows responsible for creating the gutter casts of Facies C are those of storm generated rip channels. As will be discussed below, storm generated rip channels developed in overlying facies, appear to stratigraphically terminate in a proximal location to the upper 2-3 meters of the Facies C occurrence. Where present, the gutter casts may support a punctuated, storm related, interbedding with overlying Facies D.

Pebble and coarse-sand stringers are interpreted as storm wave reworked equivalents of gutter casts. As early storm currents erode portions of the proximal inner offshore transition, they exhume previously emplaced gutter casts and subsequently reincorporate the sediment into the corresponding, newly formed, SCS bed as distinct low angle laminations.

The dominance of storm-generated bedforms, sparse bioturbation and the absence of suspension deposits, support an environment of deposition within a sandy, storm dominated system. In conventional sand-dominated shoreface environments, deposits such as these are assigned to a lower shoreface setting. However, given that this interval is of moderate grain size within the overall coarsening upwards prograding shoreface Facies Association 2, it is interpreted that this facies in fact represents deposits of a slightly more distal setting, namely that of a heavily storm dominated inner offshore transition. This interpretation is related to comments made on page 70 and will be elaborated on further in Chapter 3.1.

2.3.7 Facies C Upper Contact:

The upper contact of Facies C into overlying deposits of Facies D takes on one of two forms. In both forms, Type 1 and Type 2, contacts are laterally variable and appear to show minimal to moderate amounts of erosion. The contacts are each based on vertical and lateral variations in grain size and composition, ichnology, interpreted flow size and strength, and preservation potential.

The relatively small stratigraphic thickness of both contacts suggests a narrow depositional facies transition belt. The narrow nature of the transitions is attributed to a lack of strong return oriented flows controlled by the relatively high permeability of the overlying coarse-grained shoreface. In other words, the high permeability of the conglomeratic shoreface (Facies' D and E) effectively traps sediment in the nearshore (Carter and Orford, 1984).

The Type 1 transition is exposed at both Commotion Creek and Dokie Ridge while the Type 2 is only present at Commotion Creek. At Dokie Ridge Type 1 contacts appear to dominate, while at Commotion Creek Type 2 transitions are most common. Both transition types may also be interpreted as approximating fairweather wave base.

Type 1 Transition Observations

The Type 1 transition between Facies C and overlying Facies D is present at both Commotion Creek and Dokie Ridge. Small beds commonly 1 m in width, showing distinct normally-graded foreset laminations characterize it (Figure 2.17). The punctuated nature of this transition prevents the identification of a definitive interval thickness, however an estimate of 1.5 meters is assigned (vertical distance between lowest Facies D chert-rich conglomerate and highest Facies C quartz-dominated sandstone). The term punctuated is used to refer to the presence of multiple scours overlain by associated deposits continually cutting the tops off of previously deposited beds, while continually increasing in grain size with each successive bed upwards through the interval (Figure 2.17).

Grain size in this moderately well-sorted sandstone ranges from lower coarse to fine, with the relative percentages of both being controlled by the stratigraphic location within the overall punctuated transition (ie. the stratigraphically higher beds are coarser grained and *vice versa*). The introduction of coarse sediment is also coupled with a change in sediment composition (Figure 2.18-A). Compositionally detrital quartz is dominant in fine and smaller grain fractions, while chert dominates coarse and larger grained beds (medium sand may be either quartz, chert or lithics). Lamination dip angles are low to moderate and appear to be constant and tabular to weakly sigmoidal (Figure 2.17).

Type 1 Transition Interpretations

The Type 1 transition is interpreted as a punctuated facies change (from C to D) marked by an increase in grain size, a change in sediment composition and a transition in dominant bedding style.

The transition in grainsize is highlighted by a concurrent change in lithology. As discussed above, Facies C is dominated by very fine to fine grained quartz. Facies D is dominated by chert rich sediment (discussed below). The chert sediment ranges in grain size from medium sandstone to pebble conglomerate. This difference in grain size may suggest that throughout its lifetime, the chert-dominated sediment has been subjected to a shorter transport distance from its initial place of origin. However, although this observation is important, it does not address the possibility that both sediments could easily have been derived from underlying Gates quartz-dominated sands and chert-rich conglomerates.

The beds described above are consistent with trough cross stratification (TCS) as described by Harms et al. (1975). The TCS is a product of sand and pebble dunes migrating under the influence of fairweather, weakly to moderately asymmetric, wave energy (storm energy in this stratigraphic setting is interpreted as dominantly erosional – discussed in Chapter 3). The stratigraphic location of the TCS bedding style (directly overlying HCS inner offshore transition sandstones) represents a conformable, interfingering transition from storm dominated sandy inner offshore transition to a wave dominated lower shoreface. The proliferation of the relatively small sized bedforms supports an environment dominated by deposition, and not erosion, and hence a conformable, albeit punctuated, facies contact.

Type 2 Transition Observations

The Type 2 facies contact is only evident at Commotion Creek. This contact is characterized by the occurrence of multiple, laterally discontinuous, scour and fill structures present over an interval ranging from 0.5 to 1.5 m in stratigraphic thickness. These trough shaped scours are broad and shallow, being no larger than 14 meters in apparent width and less than 0.30 m in apparent depth. The scours, which have normally graded fills, may show evidence of wood casts, and commonly contain massive to low angle laminated, very coarse to medium sand beds rich in coalified wood fragments (Figure 2.19). The majority of elongate wood casts posses a long axis azimuthal orientation ranging between 350° and 22.5°. The upper surface of the basal coarse sand bed is sharp, and in one instance colonized by *Diplocraterion* (Figure 2.20).

The basal sands are abruptly overlain by carbonaceous, low angle laminated to rippled bedforms, in medium sand to silt sized grain fractions (Figures 2.21 & 2.22). Sand and silt rippled beds present within the Type 2 transition, are dominantly straight crested, weakly aggradational, symmetrical, 5-7 cm high (from trough to crest) and have a wavelength of 30 to 40 cm. Crest orientations range between 337° to 22.5° (Figure 2.21). The upper boundary of the rippled beds is often scoured, heralding the emplacement of the next incoming basal coarse to very coarse sand bed (Figure 2.22).

In core, the Type 1 and 2 transitions may appear very similar, however the presence of *Diplocraterion*, lower flow regime bedforms, finer grain size fractions and/or increased carbonaceous debris may indicate a Type 2 (Figures 2.18-B & 2.22).

Type 2 Transition Interpretations

The Type 2 transition represents characteristics of both high and low energy conditions. The much larger size of the trough shaped basal scour present, compared with Type 1 transition beds, suggests a larger, stronger, current. The lateral discontinuity of this transition style suggests a periodic nature of dominant controlling depositional processes (both alongshore and in a basinward direction). The episodic controls have been attributed to storm generated and driven, obliquely seaward oriented rip channels. These channels formed in response to the build-up of water inside the breakers during storm conditions (Vos, 1976). As storm wave energy increased and decreased, so would the size, and basinward extent, of the rip channels (McKenzie, 1958).

In the large rip troughs, the deposition of massive very coarse sand, and the low to flat angle of bed dip of the coarse to medium sands, indicates traction transport by dominantly erosional unidirectional currents.

These offshore oriented unidirectional rip currents are also responsible for the preferred orientation of the long axes of wood debris deposited along (and within) basal rip channel scour surfaces (and deposits). Wood clasts, as well as carbonaceous lamination material present within the low angle laminated sands, is derived from terrestrial plant remains carried seaward within the confines of the rip channels (from a storm eroding backshore)(Leithold and Bourgeois, 1984). Once entrained in the current, wood debris travels within the channel until it exceeds current competence, at which time it is laid down from the seaward weakening current (Greenwood and Mittler, 1985). As storm conditions, and current strength, wane, the current streamlines the wood debris until eventually it has no influence on clast orientation. The preferential long axis orientation of north to north-north-west is therefore a manifestation of the approximate orientation of strong unidirectional currents near their seaward terminal ends (although care is given when making this statement, as wood debris orientation could also have been influenced to a lesser degree by wave break on nearby rip channel bars).

This organic rich sand is capped by lower flow regime, low-angle laminated to rippled, medium to fine grained sands and/or silt. The presence of symmetrically rippled sandstones signifies a shift in energy regime from unidirectional to oscillatory flow. Wave conditions dominate during fairweather conditions, and hence, the ripple's formation is interpreted as representing the end of rip channel dominance (a storm enhanced state). The majority of ripples share a similar north-south crest orientation. This orientation indicates the presence of east-west migrating wave fronts. Wave migration direction itself is controlled by nearshore topography. At Commotion Creek, inner offshore to shoreface transition topography is interpreted to have been characterized by the presence of storm generated shoreface perpendicular nearshore bars (supported by the presence of rip channels). The bar crests acted as wave baffles that effectively diffracted incoming waves into similar orientations. In the lee side of these bars there existed an energy low associated with the reformation of nearshore waves. It is this low energy wave reformation that agitated the trough sediment and shaped it into bar crest parallel symmetrical ripples (Greenwood and Mittler, 1985). The post storm remobilization of nearshore bars into more shore parallel orientations, and their associated landward migration, buries the lee side, wave rippled sediment and effectively preserves the low energy deposit.

Occasionally, during waning to post storm conditions (and prior to complete fairweather bar reworking), energy conditions were low enough in the lead side of the shoreface perpendicular bars to facilitate silt deposition. The rippled texture of the silt deposit has also been attributed to a weakened wave state within the low-energy wave shadow of the storm generated shoreface bars.

The large unidirectional currents are generated by storm waves eroding and flattening the existing fairweather shoreface profile (Fox and Davis, Jr., 1978). The flattening of the profile encourages and supports the establishment of a rip channel/offshore bar state and will be discussed in greater detail in chapter 3. The episodic and variable nature of the storm system allows for the development of a highly variable energy regime. Periods of greatest wave/current intensity are dominantly erosive, but as with underlying deposits, waning storm conditions promote sedimentation.

2.3.8 Wave Dominated Lower Shoreface, Facies D Observations

Facies D outcrops at both the Commotion Creek and Dokie Ridge study areas as a prominent, resistive unit. At Commotion Creek it is dominantly bound at its lower surface by a Type 2 contacts, while at Dokie Ridge Type 1's are dominant. This unit ranges in thickness from 4 to 5 meters (Figure 2.23). It consists of kaolinite rich, well-sorted, medium to very coarse-grained chert-rich sandstones to matrix supported, moderate to moderately-well sorted, bimodal, granule to small chert pebble conglomerates. The distinguishing characteristics of this facies are the concave upwards (dominant), to planar stratified (subordinate), beds, and their respective, relative high degrees of sorting (in contrast to overlying Facies E). The concave up beds, approximately 1 m wide and up to 0.3 m in thickness, are characterized by low to moderate angle laminations which are themselves concave up in nature (Figure 2.24).

Occasionally, large scours are present. When evident they appear to be approximately 5-6 meters in width and up to 0.75 meters deep (Figure 2.25). Their primary trough long axis orientation is northeast.

2.3.9 Wave Dominated Lower Shoreface, Facies D Interpretations

The dominant concave up bedding style evident in Facies D is interpreted as trough cross-stratification (TCS). Harms (1975) attributes TCS to the infilling of scoured pits on the down-current side of migrating subaqueous dunes. The well-sorted nature of the unit suggests an environment prone to sediment reworking and bedform migration. In Facies D, migration and reworking have been attributed to a fairweather, asymmetric-oscillatory wave regime.

The source of sediment for reworking is attributed to storm emplaced lower shoreface bars. The existence of lower shoreface bars cannot be directly proven, as generally, positive topographic features on the shoreface have little to no preservation potential. However, indirect evidence for the existence of lower shoreface bars is provided in the form of the rare, large trough scours (Figure 2.25). These scours have been interpreted as preserved rip channel scours, a negative feature in the shoreface setting, and therefore a higher preservation potential. Presumably, at their time of formation, the rip channels would have been associated with rip channel flank/mouth bars.

The formation of these channels is attributed to storm enhanced, unidirectional return flows driven by storm surge and coastal erosion in the upper shoreface and foreshore regions (discussed further in Facies E – below). Up profile storm erosion transforms the beach from a more reflective to more dissipative profile. Associated with this profile transition is the establishment of the rip channel/bar system (Wright and Short, 1984). In modern coastal settings, waning and post storm (fairweather) conditions are commonly characterized by shoreface construction associated with a net landward movement of the previously storm emplaced lower shoreface bars (Davis, Jr., 1978).

Morphologically, the Facies D trough widths are smaller than the underlying scours of Type 2 Transitions, yet larger than scours described in Facies E below. This suggests that the preserved rip channel scours are gaining width as they migrate down the shoreface. The rarity of preserved Facies D rip channel scours, signifies that wave energy and channel/bar fairweather sediment reworking and remobilization are the dominant processes operating here.

The stratigraphic position of trough cross bedded Facies D, interfingering with underlying shelfal HCS to SCS sandstones, coupled with the high degree of sorting, dominant bedding style, and rip channel scours, is interpreted to represent a wave dominated, storm influenced, chert rich, lower shoreface setting.

2.3.10 Coarse Grained Upper Shoreface, Facies E Observations

Facies E is present at both Commotion Creek and Dokie Ridge and at both locations exhibits a prominent to cliff forming weathering profile. This facies gradationally overlies Facies D and is commonly 5-7 meters thick (Figure 2.22). Sedimentologically, Facies E is dominated by poorly sorted, polymodal, clast supported to sand matrix, granule to large pebble conglomerates (Figure 2.26). Generally, larger dominant sediment grainsizes are associated with more poorly sorted and polymodal facies occurrences. The uppermost meter of this facies occurrence represents the coarsest and most poorly sorted material of the Cadotte interval, and marks a change in bed dip angle from relatively steep below to relatively shallow above (Figure 2.27).

The most dominant bedding characteristics of this facies are large scale concave up clinoforms dipping approximately 20 degrees near their upper terminations and shallowing down clinoform to approximately 7-10 degrees. The clinoforms range in strike from east-west to southeast-northwest (Figure 2.23 & 2.26). Often, along an outcrop face, the dip angle of these clinoforms appears to vary, commonly this is just an issue of perspective controlled by the intersection of the surface's strike with the outcrop face orientation, however occasionally a clinoform does have a somewhat more shallow upper clinoform dip of approximately 10 degrees.

Other common bedding characteristics include trough scours averaging approximately 1 to 2 meters in width, and 30 to 50 cm in depth, and small concave down surfaces that onlap, both up and down dip, onto a larger basal clinoform (Figures 2.23 & 2.26).

2.3.11 Coarse Grained Upper Shoreface, Facies E Interpretations

The large clinoforms characteristic of Facies E are interpreted as being representative of the shoreface dip profile at various moments in time. Their common steep dip, coupled with the coarse nature of the sediment and the numerous high energy indicators (throughout almost all facies) suggests a more reflective type shoreface profile (Wright and Short, 1984). The steepness of coarse grained shorelines is a common result of increased shoreface permeability. High seepage rates associated with the coarse shoreface inhibts the basinward migration of significant volumes of sediment, and in effect, traps it in the nearshore zone (Carter and Orford, 1984). Occasionally, more shallow dipping profiles are present. These have been interpreted as being representative of storm ravinement surfaces. When storm enhanced waves impact the proximal nearshore they have a strong erosive tendency that manifests itself as rip channel-bar system (Hunter et al., 1979). In other words a change in shoreface morphodynamic state accompanies fluctuations in nearshore wave energy (Wright and Short, 1984).

The other common bedding styles present (large trough scours, and concave down surfaces) are both diagnostic of the storm, and immediate post storm, state of the nearshore (Hunter et al., 1979). The trough scours are interpreted as the proximal expression of the rip channels responsible for the development of Type 2 transitions (discussed above). The formation of these rip channels is controlled by the shallowing of the shoreface profile due to impacting storms. Gruszczynski et al. (1993) reports rip channels as being absent from steep reflective beaches, however the increased water mass piled upon the beach, coupled with the shallowing of the shoreface profile, during storm conditions allows for the development, and sustenance, of the rip channel – bar system. The trough scours appear to have an apparent long axis azimuthal orientation of east-northeast, west-southwest (however 3-dimensional exposures were not common and therefore this statement is difficult to support with a high level of certainty). If this orientation is taken as an approximation of channel long axis direction then it may be assumed that rip channel orientation in more shoreline proximal settings is close to shore-parallel, while in more distal reaches of the nearshore they have turned in a more shore oblique direction.

The concave down surfaces present in Facies E are interpreted as representing nearshore storm generated bars that have been welded back onto the upper shoreface during more constructional, post storm, periods of coastal evolution.

The poorly sorted upper meter or so of the facies occurrence has been interpreted as a plunge step. It marks not only a decrease in grain size, but also a change in shoreface profile from the relatively steeply dipping upper shoreface to the shallower bedded lower foreshore (Hart and Plint, 1989). The formation of this step has been interpreted as representing a zone of interaction between breaking waves and backswash (Massari and Parea, 1988).

The steeply dipping shoreface clinoforms, two dominant bedding styles and presence of an upper plunge step, supports a Facies E interpretation of an upper shoreface.

2.3.12 High Energy Foreshore, Facies F Observations

Facies F is present at both the Dokie Ridge and Commotion Creek study areas. On average it composes the uppermost 4 meters of the prominent ridge/cliff-forming portion of the outcrop sections. The unit exhibits sharp lower and upper contacts (Figure 2.27). These contacts mark a distinct and visible increase in sediment sorting, grain size and bedding style from that evident in both under and overlying facies. The basal facies transition is sharp and characterized by a transition from poorly sorted, coarse grained, polymodal conglomerates of upper Facies E, to well sorted, low angle laminated sandstones and conglomerates of Facies F (Figure 2.27).

The dominant sedimentologic, and lithologic features of this facies are distinct, sharp based, inversely graded, low angle plane beds (dipping 3-6 degrees), consisting of alternating variations of well to very well sorted, chert-rich, coarse to very coarse grained sandstones with well sorted, uni to bimodal, clast supported, chert granule to small pebble conglomerates (Figure 2.28-A&B). A rare feature of the conglomerate beds is the preservation of imbricated, cigar shaped, small to medium pebbles. When present, the pebbles appear to dip towards the northeast (Figure 2.28-C). The relative percentage of coarse to very coarse sandstone beds, compared to conglomerate beds, appears to increase towards the top of the facies occurence. Occasionally, local bedding dip angles may decrease in the uppermost meter of the section (to about 3 degrees), but this is by no means a diagnostic feature of the low angle plane beds.

The uppermost few beds of the unit may exhibit a darker color associated with an increase in the integration of comminuted carbonaceous material into the matrix of the rock.

2.3.13 High Energy Foreshore, Facies F Interpretations

The dominance of sandstone and conglomerate low angle to flat, planar beds is indicative of deposition under upper flow regime conditions (Harms et al, 1975). The presence of these planar beds lying directly on top of poorly sorted upper shoreface deposits suggests deposition in a foreshore setting (Hart and Plint, 1989). This region of the coastal system is characterized as being located between low-low tide and the upper limit of storm wave swash (Hart and Plint, 1995). When incoming waves enter a region where water depth is as deep as the waves are high, they break (Komar, 1976). Wave breaking transforms the arriving energy agent from a wave-form, to sheet flow. Due to the steepness of the coarse Cadotte shoreface, it is thought that the wave to swash transition would be dominated by either plunging or surging breakers (depending upon the steepness of the incoming wave) (Komar, 1976).

High sediment infiltration rates, controlled by the high permeability of coarse grained beach material, prevent the development of a strong backswash associated with the seaward directed return flow of the collapsed wave water mass (Sellinger Jr., 1981). The absence of a strong backswash encourages the development of inclination on the seaward dipping beach plane beds, relative to finer grained coastlines (Carter and Orford, 1984).

The occasional presence of pebble imbrication provides evidence of a wave approach direction from the northeast, as generally, long axes of clasts dip preferentially seaward (Massari and Parea, 1988; Hart and Plint, 1989). Inverse grading, more common of the planar beds than clast imbrication, is attributed to the process of kinetic sieving which occurs during swash (Middleton, 1970).

The carbonaceous material in the matrix of the uppermost beds of this facies is derived from wood debris stranded at the upper reaches of the beach (at the landward limit of wave swash). Its presence could reflect stranding of wood debris associated with either fairweather high tide conditions, or the landward extent of a storm enhanced foreshore (above the landward limit of normal fairweather foreshore deposits) deposited during waning storm conditions.

The well sorted, coarse and cherty nature of Facies F sediment allows for the development of large pore throats that tend to be preserved during post deposition burial, compaction, pressure solution and cementation (Moslow, 1994). It is the preservation of a portion of these original pore throats that allows for the high reservoir potential of preserved, coarse grained, Lower Cretaceous foreshores (Moslow, 2000).

2.3.14 Storm Influenced Backshore, Facies G Observations

The transition from the stratigraphically lower Facies F to Facies G is sharp and inclined (Figure 2.27-C). This facies is characterized by poorly sorted, sand matrix to matrix supported (with occasional basal clast supported), polymodal, granule to medium pebble conlglomerate (Figure 2.27-C). The conglomerate is dark on fresh surfaces due to a high concentration of comminuted carbonaceous debris. Locally, horizons exhibiting relatively higher concentrations of this carbonceous debris are also present. Drillhole #1 and Gulf Trefi 80-01 are the only examples of fully exposed Facies G intervals. The interval in Drillhole #1 is 1.65 m thick and is composed of what appears to be two normally graded deposits, each showing an increased concentration of carbonaceous material at their respective upper boundaries. The upper bed also appears to be slightly finer grained than the underlying bed (Figure 2.29 A). In Gulf Trefi 80-01 the unit is 1.25 m thick and does not contain the obvious carbonaceous concentrations evident in Drillhole #1. Instead, a single, poorly sorted, coarse grained, pebbly sandstone bed characterizes the unit.

Petrographically, Facies G is rich in both alluviated clays and kaolinite (Figure 2.29 B and C).

2.3.15 Storm Influenced Backshore, Facies G Interpretations

The poor sorting, polymodal, and sand matrix, to matrix supported, nature of Facies G indicates rapid sedimentation not prone to sediment reworking and continued agitation after deposition. The presence of two individual moderately normally graded packages present in Drillhole #1 indicates the decreasing competency of the transporting agent responsible for the emplacement of each bed. As well, the finer grained nature of the upper of the two normally graded beds may reflect either a weaker transporting agent (less powerful storm generated current) or, a greater distance from the sediment source (eg. greater transport distance from the active shoreface)(Orford and Carter, 1982). The variable thickness of this facies (between Drillhole #1 and Gulf Trefi 80-01) indicates that the depositional process was inconsistent in behavior with respect to normal progradation of the shoreline. This facies is interpreted to be the product of upper flow regime wave-generated current transport characterized by plane beds and normal grading driven by storm washover sedimentation occurring in a backshore setting. Limited exposure prevents a concise depositional geometry from being ascertained (eg. washover fans vs. a washover flat). Orford and Carter (1982) indicate that variations in backshore deposit geometries are related to variations in volumes of swash that pass over the beach crest. This suggests that in the Cadotte system, where numerous storm events are interpreted to have occurred, both geometries are probably present in variable concentrations. As well, due to the coarse nature of Cadotte sediment, it is likely that any washover fans present would have a different, and somewhat more restricted, morphology than their finer grained equivalents (Deery and Howard, 1977).

The high concentration of carbonaceous debris has been interpreted to represent the degradation and incorporation of moderate to large amounts of wood debris disseminated throughout the matrix of the deposit. The high concentrations of carbonaceous material at the upper bed boundaries indicate a larger amount of wood debris remaining on the surface of the underlying bed after the storm repsonsible for the emplacement of the bed passed, and therefore the transporting agent had been withdrawn. In essence, the extremely carbonaceous rich horizons represent wood lags marking the start of waning storm conditions.

The alluviated clays are associated with the high primary depositional permeability of the backshore sediments, and are introduced via the downward percolation of clay rich meteoric water (Moraes and De Ros, 1990). Their presence indicates a period of exposure at the upper contact of the facies interval (Moraes and De Ros, 1992).

2.3.16 Facies Association 2 – Facies Association 3 Transition Observations

The transition from Facies Association 2 to Facies Association 3 is variable in nature. At neither the Dokie Ridge nor Commotion Creek study areas is a continuous transition exposed, and hence lithologic evidence for the transition was derived from the Drillhole #1 and Gulf Trefi 80-01 core.

The outcrop does provide minor input to analysis of the transition in the form of weathering profiles. At the Commotion Creek study area the transition from one association to the next is accompanied by a change in weathering profile from the prominent, ridge/cliff forming units of Facies Association 2 to the recessive and often covered outcrops of Facies Association 3 (Figure 2.30-C). At Dokie Ridge, the uppermost bedding plane surface of the underlying Facies Association 2 (Facies G), has an extensive and somewhat systematic, undulating appearance (Figure 2.30-A). Descriptively, the undulatory bedform appearance is somewhat analogous to an upside down egg carton; it is composed of a series of 3-dimensional pits and mounds - the pits being up to 0.35 meters in depth, with respect to the top of the mounds.

In both the Drillhole #1, and Gulf Trefi 80-01 cores, the transition from Facies G (Facies Association 2) to Facies Association 3 is sharp and marked by a lithologic transition from coarse/very coarse, carbonaceous rich, cherty sandstone to dark, organic rich shale . (Figure 2.30-B)

2.3.17 Facies Association 2 – Facies Association 3 Transition Interpretations

The variation in weathering profiles between outcropping units of Facies Association 2 and Facies Association 3 is indicative of a transition from a resistant to recessive lithology. This interpretation is supported by the lithologic expression of this transition in the two drill cores, as shale rich units would be less resistant to surficial weathering process than the underlying conglomerates.

The undulatory nature of the upper surface of Facies G at Dokie Ridge has been interpreted as a scour/erosive surface characterized by sediment reworking. The egg carton like appearance of the bedding surface represents the mobilization of sediment (possibly as gravel dunes), however the lack of a preferential migration direction indicates that the erosive current lacked the ability to effectively remove much, if any, of the actual coarse grained unit. In the absence of biostratigraphic support the temporal gap associated with the surface is impossible to determine. It could represent as little as a couple of years, or as much as a few million years.

The lithologic change from coarse high energy, chert rich deposits to low energy, fine grained shales indicates a decrease in flow regime. This decrease has been attributed to flooding of the coastal plain associated with the establishment of a nearshore bay. The lack of any intertidal deposits between the shales and sandstone/conglomerates may represent either rapid flooding or early erosion of a non-lithified substrate.

2.4 Transgressive Barrier Island System, Facies Association 3 – The Walton Creek Interval

The Walton Creek interval (Facies Association 3 – FA 3), although subdivided, is not discussed in as much detail as the Cadotte succession due to both limited available data, and the focus of the study. Data for the description of Facies Association 3 comes from one or two scattered outcrops at Commotion Creek, Commotion East and Commotion West, as well as cored intervals in Drillhole #1 and Gulf Trefi 80-01.

An outcrop bench capping the conglomerate cliff face at Commotion West represents the largest outcrop section assigned to this Facies Association. The bench is recessed north of the cliff face by approximately 5 to 15 m and consists of three FA 3 litho-units; L1, L2 and L3 (Figure 2.31). A fourth unit (L4) of indeterminable thickness is described from the drillcores of both Drillhole #1, and Gulf Trefi 80-01.

2.4.1 Transgressive Barrier Island System, Facies Association 3 – Basal Walton Creek Member Observations

Due to poor exposure, only a speculative stratigraphic thickness for L1 of <1 m could be obtained from the Commotion West bench. However, a more accurate thickness of 40 cm is provided from Drillhole #1 core. L1 is a recessive shale bed that is non-descript, extremely fractured and can be seen abruptly overlying the top of the underlying Facies Association 2 conglomerate interval recovered in both the Drillhole #1 and Gulf Trefi 80-01 cores.

L2 is approximately 0.5 to 1.5 m thick and is laterally continuous for up to 50 m. Beyond 50 m outcrop preservation is low, and as such, a definitive lateral extent cannot be determined. L2 sharply overlies L1 and consists of rooted, wood debris rich, fine grained sandstone with variable concentrations of silt and argillaceous material (Figure 2.31). The unit contains a monospecific assemblage of *Arenicolites*, but although common, the burrows do not occur in a high enough concentration to completely destroy the primary sedimentary fabric.

A dominant bedding style for L2 is difficult to ascertain, but the unit does contain prolific wispy and scattered ripple laminations overlying gently inclined tabular beds (Figure 2.31). Spatially, L2 is correlative with L1 below, L4 laterally, and L3 above.

L3 sharply overlies L2 and is marked by the abrupt appearance of granules to small pebbles (Figure 2.31 B). These granules and pebbles demarcate the basal laminations of trough cross-stratified, coarse to very coarse sandstone beds (Figure 2.31). Over a vertical distance of 1 m, this very well-sorted, pebble-rich sandstone bed gradationally becomes a very well-sorted, clast supported, granule to small pebble conglomerate. Dominant bedding style within the conglomerate appears to change, from trough cross bedding below, to planar bedding at the top of the outcrop section (Figure 2.31).

The final Walton Creek litho-unit is L4. This unit has been described in detail by Giggs (2001), and therefore will not be given much focus here. It consists of interbedded sandstones, siltstones and shales rich in carbonaceous material and siderite (Figure 2.32). These units show evidence of intense burrowing, rare wave ripples and sharp lithologic transitions. The unit is present in both drill cores and therefore may be laterally persistent with respect to the scale of the study area.

2.4.2 Transgressive Barrier Island System, Facies Association 3 – Basal Walton Creek Member Interpretations

The L1 shale is indicative of suspension sedimentation, and due to its apparently persistent lateral extent, as well as the character of overlying units, has been attributed to deposition in a restricted coastal bay or lagoon. The presence of this unit directly, and sharply, overlying the Cadotte conglomerate represents a coastal flooding event, and consequently, the basal surface of the L1 unit is classified as a flooding surface.

Flooding surfaces are indicative of increasing water depth associated with shoreline transgressions (Posamentier and Allen, 1999). The lack of any basal coarse-grained material associated with this flooding surface may suggest that the amount of erosion associated with transgression was minimal.

The presence of rooting and a mono-specific *Arenicolites* assemblage in L2 suggests stressed shallow water conditions. The inclined sandstone beds have been interpreted as foreset accretion surfaces on a larger sedimentary macroform developed within the restricted bay/lagoon of L1. Wispy rippled tops signify either a decrease in current velocity vertically upwards through the unit, or sediment agitation during periods of lower energy than that responsible for the generation of the larger macroform (upon which they formed).

The spatial relationships of L2, coupled with the unit's sedimentary expression, supports an environment associated with a nearshore bay and barrier island system, however care is taken in the detailed environmental allocation as the small amount of available data on the unit fits a couple of relevant environmental interpretations; namely sandy submerged bar, tidal delta or sandy backshore/washover. The lack of an overlying sand dominated barrier (as opposed to the gravel system actually present) weakens support for washover sediment, as the majority of storm washover sediment (in this case sand) is normally derived from erosion of an upper shoreface and forshore (in this case gravel). As well, the presence of a monospecific assemblage of *Arenicolites* in L2 is tough to envision in the washover scenario. A lateral unit association with bayfill deposits may strengthen support for some form of sandy tidal delta, however the lack of any obvious tidal structures within the unit effectively weakens this interpretation. As well, the fact that, again, there is no obvious source for sand in the preserved overlying shoreface sediments of L3 also poses a problem. A shallow, rooted sand bar formed in a restricted bay behind a gravel barrier-island is therefore interpreted as the most likely interpretation.

The L3 vertical succession of basal trough cross bedded sandstones (lower shoreface), gradationally overlain by trough cross bedded granular conglomerates (upper shoreface) and finally planar bedded conglomerates (foreshore), is interpreted as a thin shoreface succession. The predominance of trough cross-stratification, and high degree of sediment sorting within the lower and upper shoreface sub-environments indicates frequent sediment agitation and mobilization within a wave-dominated setting. The presence of planar-bedded conglomerate capping L3 is interpreted as a swash zone/foreshore characterized by upper flow regime sheet flow. This shoreface model is similar to the one discussed for Facies Association 2, however on a somewhat smaller scale.

The lack of lateral continuity of the L3 interval suggests that the shoreline complex was relatively isolated. This isolation supports a barrier-island as the most likely shoreline/shoreface morphology (Reinson, 1992), and therefore, L3 is interpreted as a prograding, gravelly, wave-dominated barrier-island.

L4 has been assigned the interpretation of a subtidal bayfill by Giggs (2001) and will not receive further interpretation here.

The relatively thin nature of the L3 barrier island (compared with the underlying Cadotte shoreface), coupled with the absence of any underlying shelf deposits (ie. Facies A, B and C in the stratigraphically older Cadotte succession) is indicative of a decrease in shoreline accommodation space associated with a shoreline succession rapidly retreating over existing nearshore deposits (compared with shoreline progradation over offshore transition deposits characteristic of FA 2). This juxtaposition of barrier-island over restricted bay/lagoon is common to shorelines in a state of transgression (Curray, 1964), and therefore a coastline in a state of retrogradation (Galloway and Hobday, 1983). In interpreting the shoreline as being in a state of transgression, it is important to recognize that the temporal significance of a sea level change is much greater than that of the more temporally insignificant daily, seasonal, and yearly progradation of the barrier-island. For this reason, although regional coastal setting is in an overall state of retrogradation, the barrier itself is in fact progradational. Simply put, a temporally small-scale highstand may occur within the temporally large-scale transgression (Davis Jr. and Clifton, 1987; Nummedal and Swift, 1987).

Table 2.1 - Facies Association and lithostratigraphic summary table. Facies Association thicknesses are only provided for those portions of each association discussed in this study, and therefore, do not represent a complete lithostratigraphic thickness for either the Gates Formation or Walton Creek Member.

Facies Association #	Formation or Member	Sedimentary Characteristics	Approximate Thickness	Interpretation
3	Walton Creek Mbr.	Shales, Siltstones, Rippled, Rooted & Burrowed Quartz Sandstones & Trough to Planar Bedded Granular Conglomerates	6-7 m	Brackish Bay and Gravel Dominated, Transgressive, Wave Dominated Shoreface (Barrier Island?)
2	Cadotte Mbr. & Hulcross Fm.	Outlined in Table 2.2	83.5 m	Distal Ramp, Storm Dominated Offshore Transition & Prograding, High Energy, Coarse Grained, Shoreface (Strandplain)
1	Gates Fm.	Dominately U.V.F. Grained Quartz Rich HCS to SCS Sandstone Beds that grade upsection into to Macaronichnus Rich TCS beds. These Macaronichnus beds are capped by a Sharp Scour associated with the emplacement of Chert Conglomerate Gravel Dunes.	17 m	Lower to Middle, Storm Dominated Sandy Shoreface. Shoreface Succession has been Transgressively Eroded & Partially Reworked into Gravel Dunes (Associated with a Rise in Relative Sea Level).

Figure 2.1 - Core description (A) and photo mosaic (B – following page) from Drillhole #1. Core shows individual facies of Facies Association 2: Facies C in yellow, C-D transition in blue, D in red, E in orange, F in Blue, G in white, as well as overlying Facies Association 3 (in Grey). Cadotte interval is characterized by a coarsening up grain-size profile concurrent with a change in lithology from quartz sandstone to chert sandstones and conglomerates. Top of Cadotte Member is unconformable with overlying Walton Creek (although not illustrated in striplog). Facies Association 2 color code is also outlined in Table 2.2.

A

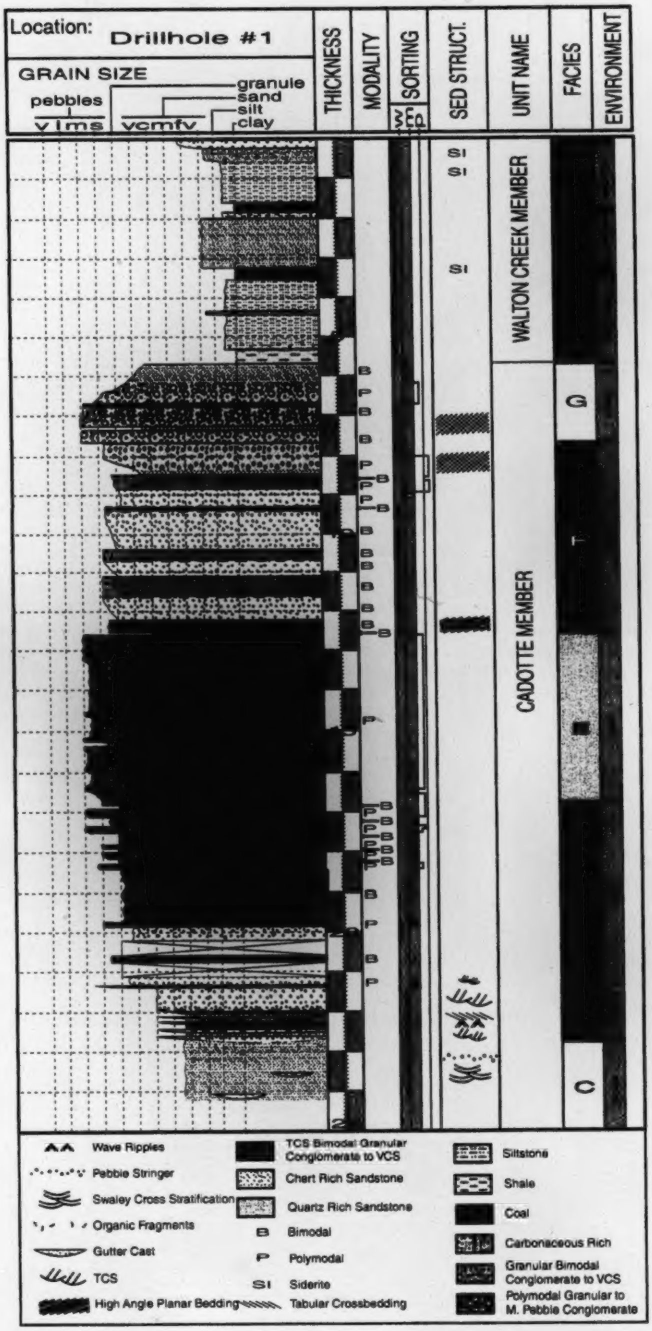

Location: Drillhole #1
GRAIN SIZE
pebbles
v l m s
v c m f v
granule
sand
silt
clay
THICKNESS
MODALITY
SORTING
SED STRUCT.
UNIT NAME
FACIES
ENVIRONMENT
SI
SI
SI
WALTON CREEK MEMBER
CADOTTE MEMBER
G
C
B
P
Wave Ripples
Pebble Stringer
Swaley Cross Stratification
Organic Fragments
Gutter Cast
TCS
High Angle Planar Bedding
TCS Bimodal Granular Conglomerate to VCS
Chert Rich Sandstone
Quartz Rich Sandstone
Bimodal
Polymodal
Siderite
Tabular Crossbedding
Siltstone
Shale
Coal
Carbonaceous Rich
Granular Bimodal Conglomerate to VCS
Polymodal Granular to M. Pebble Conglomerate

Figure 2.1 - B) Photo mosaic of core from Drillhole #1 annotated with color codes shown in Figure 2.1 A.

B

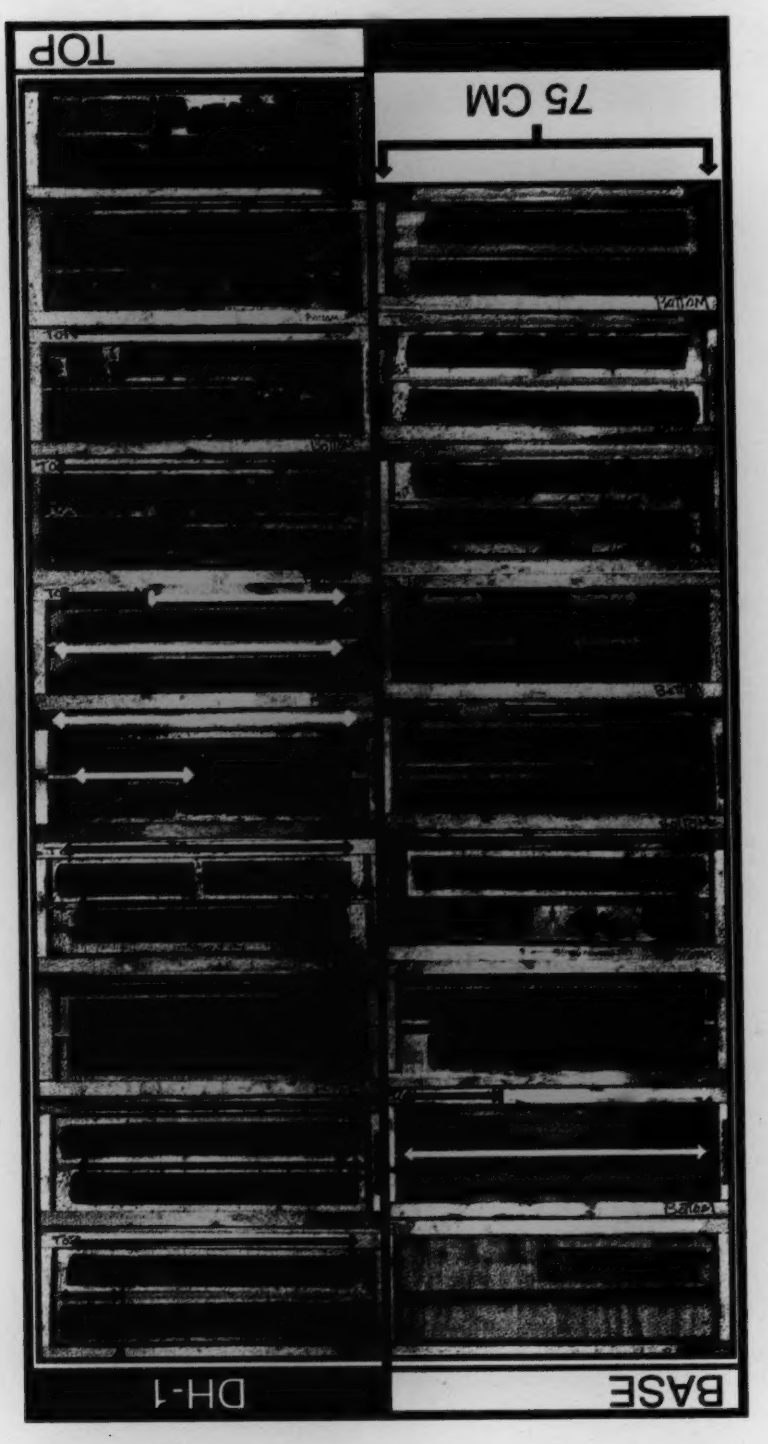

TOP
75 CM
BASE
DH-1

Table 2.2 - Summary table for Facies Association 2 (Hulcross and Cadotte units). Facies colors relate to Figure 2.1. Thicknesses marked with a "~" indicate a lower level of certainty in the value relative to other facies. O.S.T. – Offshore Transition, L.S.F. – Lower Shoreface, U.S.F. – Upper Shoreface, F.W.W.B. – Fairweather Wave Base, HCS – Hummocky Cross Stratification, SCS – Swaley Cross Stratification, V.C. – Very Coarse Grained.

G	Poorly Sorted, Polymodal, Coarse Grained, Carbonaceous Rich, Chert Conglomerates	1-6 m?	Storm Influenced Backshore
F	Low Angle to Flat Bedded, Uni to Bimodal Granular Conglomerates & V.C. Sandstones	3-5 m	High Energy Foreshore (Swash Zone)
E	Chert Dominated, Polymodal, Coarse Grained, Poorly Sorted, Rip Channels, Bars, & Clinoforms	5-7 m	High Energy, Coarse Grained U.S.F. (& Plunge Step).
D	Moderate to Well Sorted, Chert Dominated, V.C. Sandstone & Granular Conlgomerate Trough Cross Beds	4-6 m	Wave Dominated, L.S.F. (above F.W.W.B.)
TZ 1	Mixed Fine Quartz & Medium to Coarse Chert, Trough Cross Bedded Sandstones	1-1.5 m	Gradational, Inner O.S.T./L.S.F. Transition (approx. F.W.W.B.)
TZ 2	Large Shallow Scours, Coalified Woody Debris, Symmetrical Ripples in both Chert Sandstones & Siltstones	1-1.5 m	Sharp, O.S.T./L.S.F. Transition - Rip Channel Terminal Ends (approx. F.W.W.B.)
C	HCS to SCS Bedded Quartz-Rich Sandstones, with Pebble Filled Gutter Casts, & Coarse Sand to Pebble Stringers	15-20 m	Storm Dominated, Sand Rich, Inner O.S.T., (above Storm Wave Base)
B	HCS & Planar Bedded Sandstones Interbedded with Siltstones & Shales	~ 30 m?	Storm Influenced, Mixed, Outer O.S.T., (above Storm Wave Base)
A	Laminated Siltstones & Shales	~ 14 m?	Mud/Silt dominated Distal Ramp (below Storm Wave Base)

Figure 2.2 - A) Chert-rich gravel beds within Hummocky and Swaley cross stratified quartz dominated sandstones. B) Close-up of an individual conglomerate bed, note the sharp top and base, as well as the inconsistent thickness, characteristic of the conglomerate interbeds. Both photos are from Dokie Ridge.

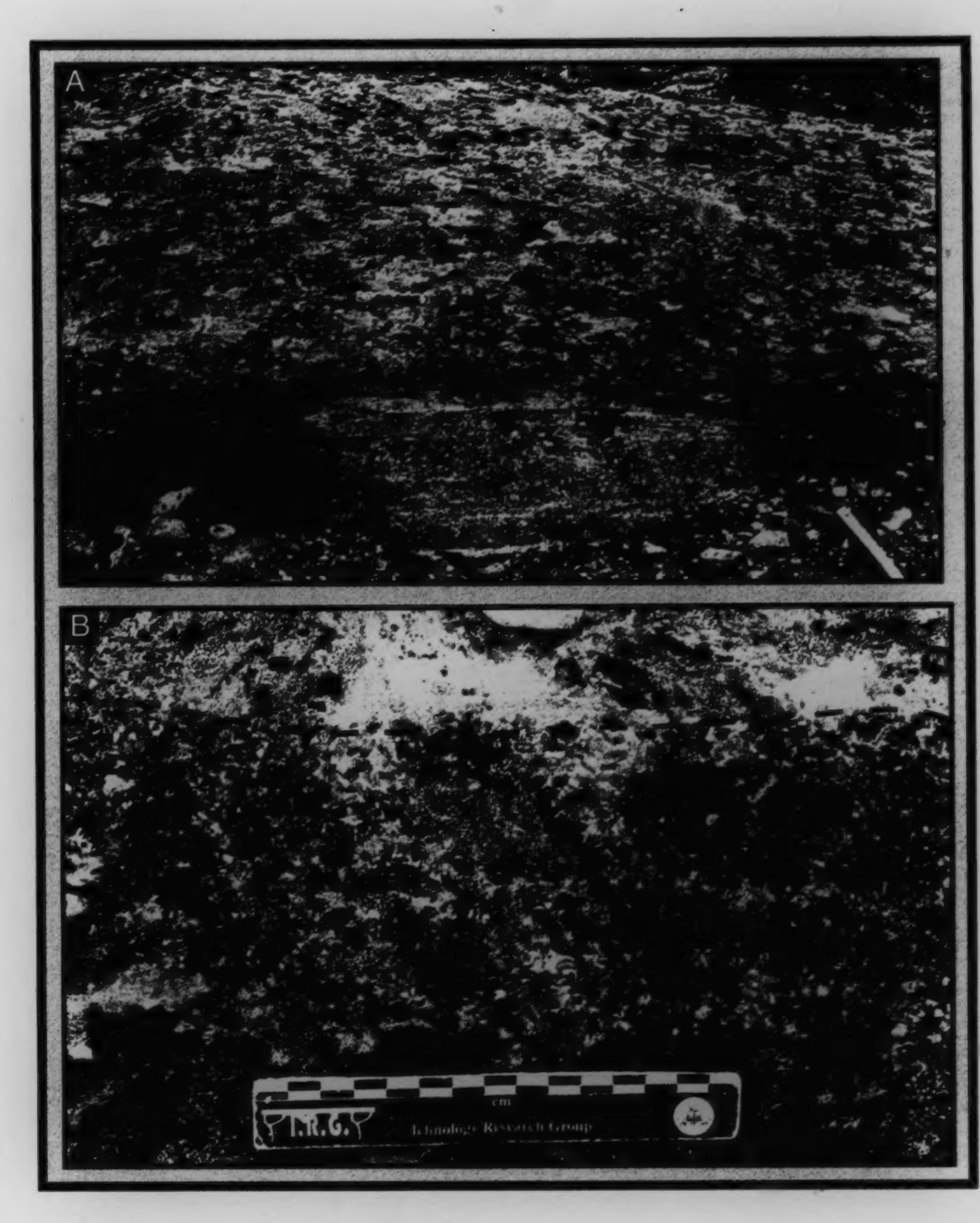

A
B
cm
I.R.G.
Ichnology Research Group

Figure 2.3 - Characteristics of the Upper Gates Interval. A) Gravel Dunes on a bedding surface. B) Cross section of the Upper Gates showing lower Trough Cross Stratified – *Macaronichnus* Interval (TCS-MI), erosionally overlain by a Basal Lag (BL) interpreted as a transgressive lag, chert rich Tabular Beds (TB), and finally Gravel Dunes (GD). C) Intense *Macaronichnus segregates* (Ma) in TCS sandstone. Photos are from Dokie Ridge.

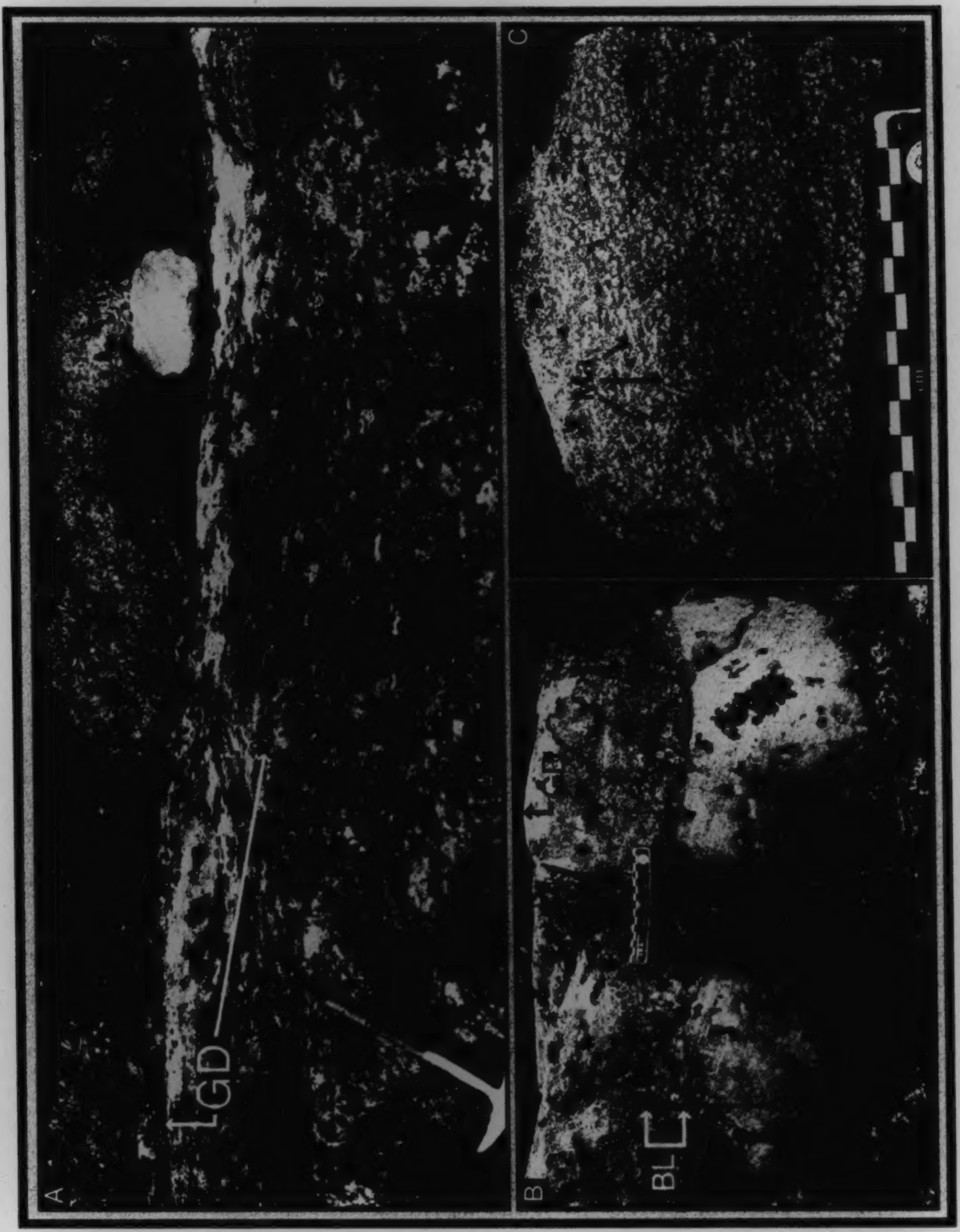

A
GD
B
BL
GB
C

Figure 2.4 - Lithologic strip log of the Upper Gates. Environments: LSF – Lower Shoreface, MSF – Middle Shoreface, DR – Distal Ramp. Lower conglomerate is interpreted as a coarse grained tempestite. Transgressive surface of erosion is present at the base of the lag capping the Gates lower shoreface. Section is described from outcropping Gates at Dokie Ridge.

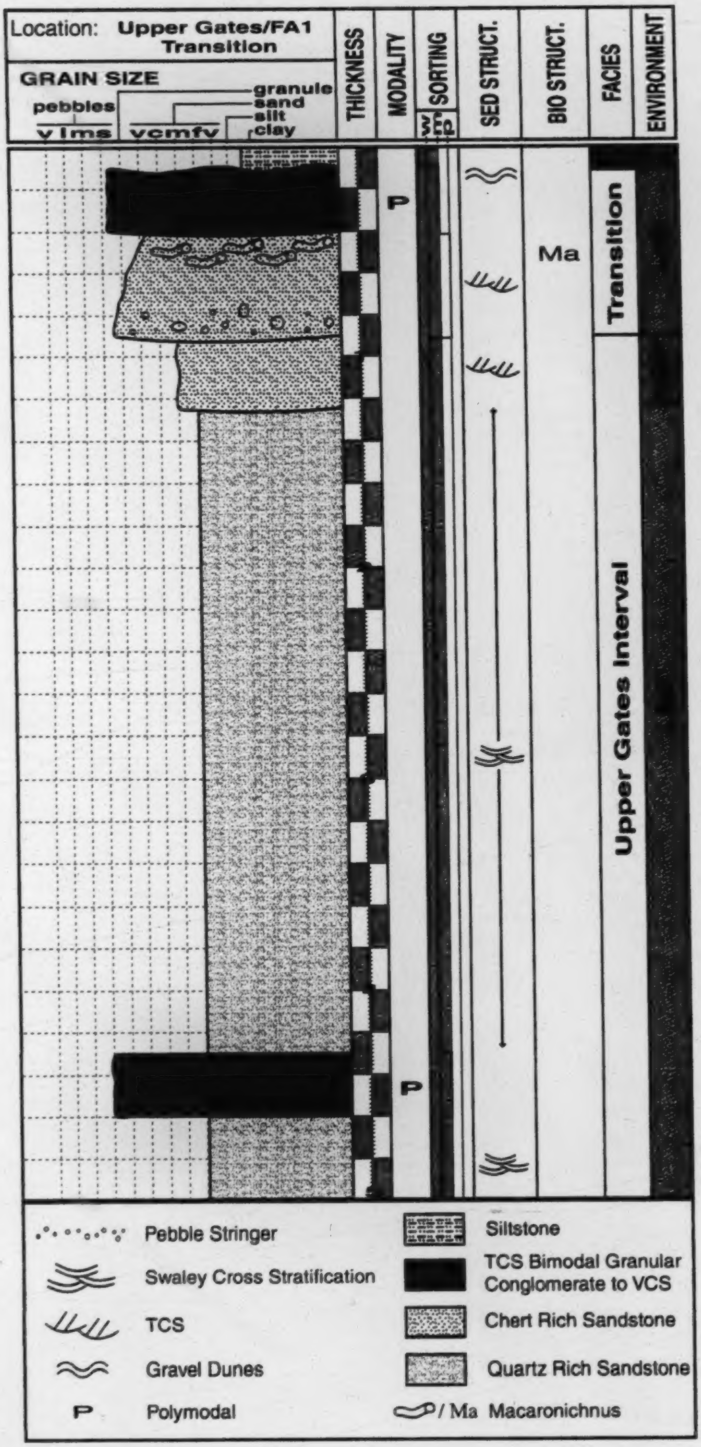

Location: Upper Gates/FA1 Transition
GRAIN SIZE
pebbles
v l m s
v c m f v
granule
sand
silt
clay
THICKNESS
MODALITY
SORTING
w
m
p
SED STRUCT.
BIO STRUCT.
FACIES
ENVIRONMENT
P
Ma
Transition
Upper Gates Interval
P
Pebble Stringer
Swaley Cross Stratification
TCS
Gravel Dunes
P Polymodal
Siltstone
TCS Bimodal Granular Conglomerate to VCS
Chert Rich Sandstone
Quartz Rich Sandstone
/ Ma Macaronichnus

Figure 2.5 - Hulcross carbonaceous-rich siltstone from Dokie Ridge. A) Cross section photo of laminated siltstone and shale. B) Thin section photo at 10X magnification.

A
B
DR-1T Hulcross Siltstone
1 mm
Olympus BH 04 Obj.

Figure 2.6 - Outcrop of Facies B at Lower Commotion East. A) Section shows approximately 50% sandstones and 50% siltstones and shales. B) Sand beds vary in thickness and occasionally show evidence of anomalous mounding.

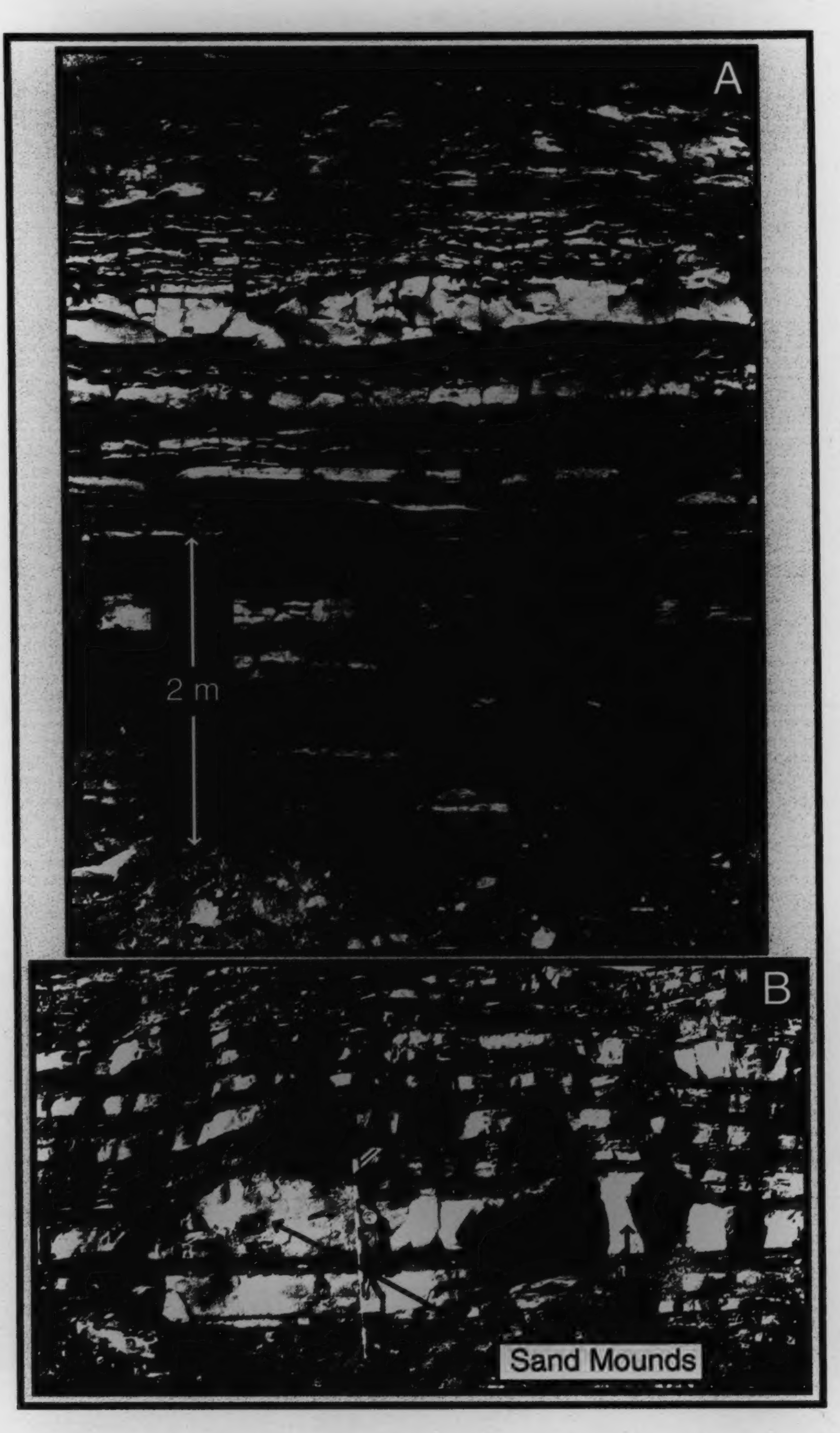

A
2 m
B
Sand Mounds

Figure 2.7 - Fairweather ichnology at Lower Commotion East. Fairweather ichnology in very fine-grained sandstones is represented by; A) *Chondrites* (cross section view), B) *Gyrocorte* (surface bedding plane view), C) *Muenstaria* (surface bedding plane view), and D) *Thalassinoides* (basal bedding plane view).

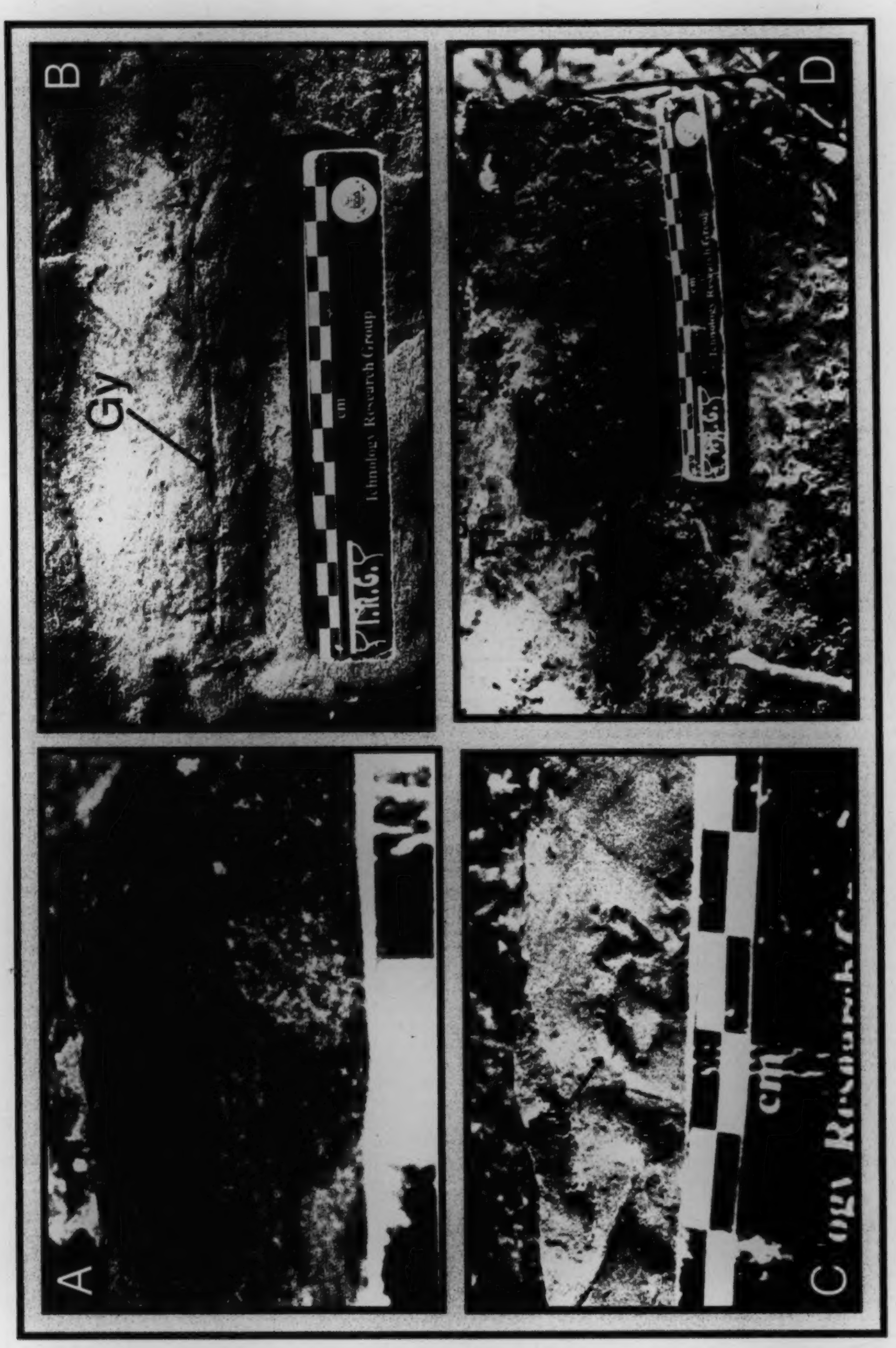

A
B
C
D
Gy
cm
Technology Research Group

Figure 2.8 - Diagenetic characteristics (A, B, C) and coal accumulation (D) common to Facies B (Hulcross). Siderite pebbles often mantle the basal surfaces of low angle laminated sandstone beds (A) but can also occur in concretionary horizons (C). Diagenetic Pyrite (B) is also common. D) A single thin, yet laterally continuous, coal seam is located within the lower reaches of the section and signifies an offshore accumulation of woody and plant debris.

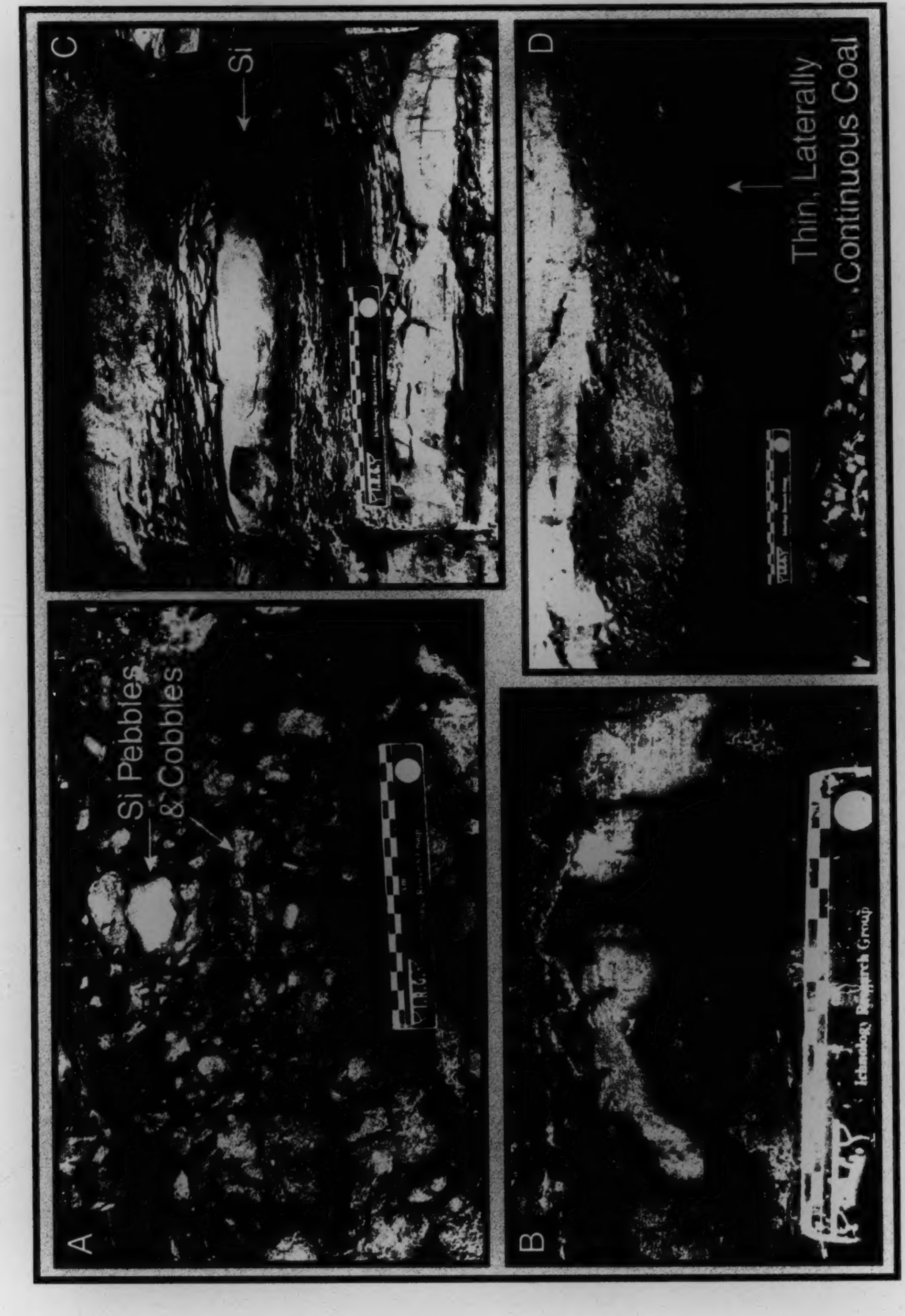

A
Si Pebbles
& Cobbles
B
Ichnology Research Group
C
Si
D
Thin, Laterally
Continuous Coal

Figure 2.9 - Burrowed sediments in Facies B (Hulcross). A) Sparse *Planolites* and *Schaubcylindrichnus* in laminated sandstones. This sparse colonization indicates that an environmental stress existed (high sedimentation rate?) which prohibited organisms from totally reworking the deposit. B) Sediment completely biogenically reworked by *Phycosiphon* and *Chondrites*, indicating conditions more favorable to biologic colonization than ripple laminated deposit.

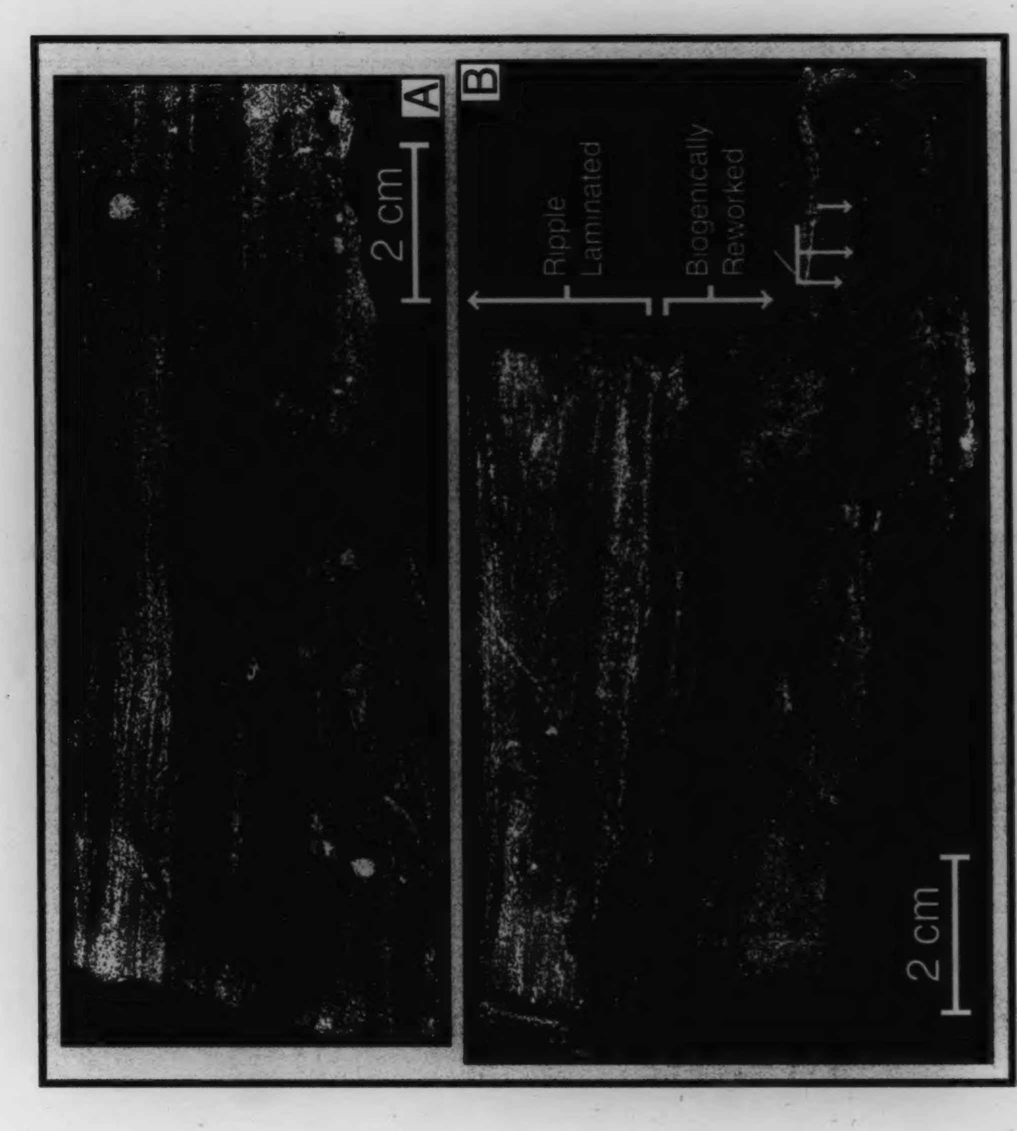

A
2 cm
B
Ripple Laminated
Biogenically Reworked
2 cm

Figure 2.10 - Laminated sandstones of Facies B (Hulcross) take one of three forms; A) Planar to flat laminated, B) Low angle laminated and C) Ripple laminated. Low angle laminated sandstones are interpreted as hummocky cross stratification (HCS). A and B are interpreted as tempestites while C represents decreasing flow intensity during waning storm conditions.

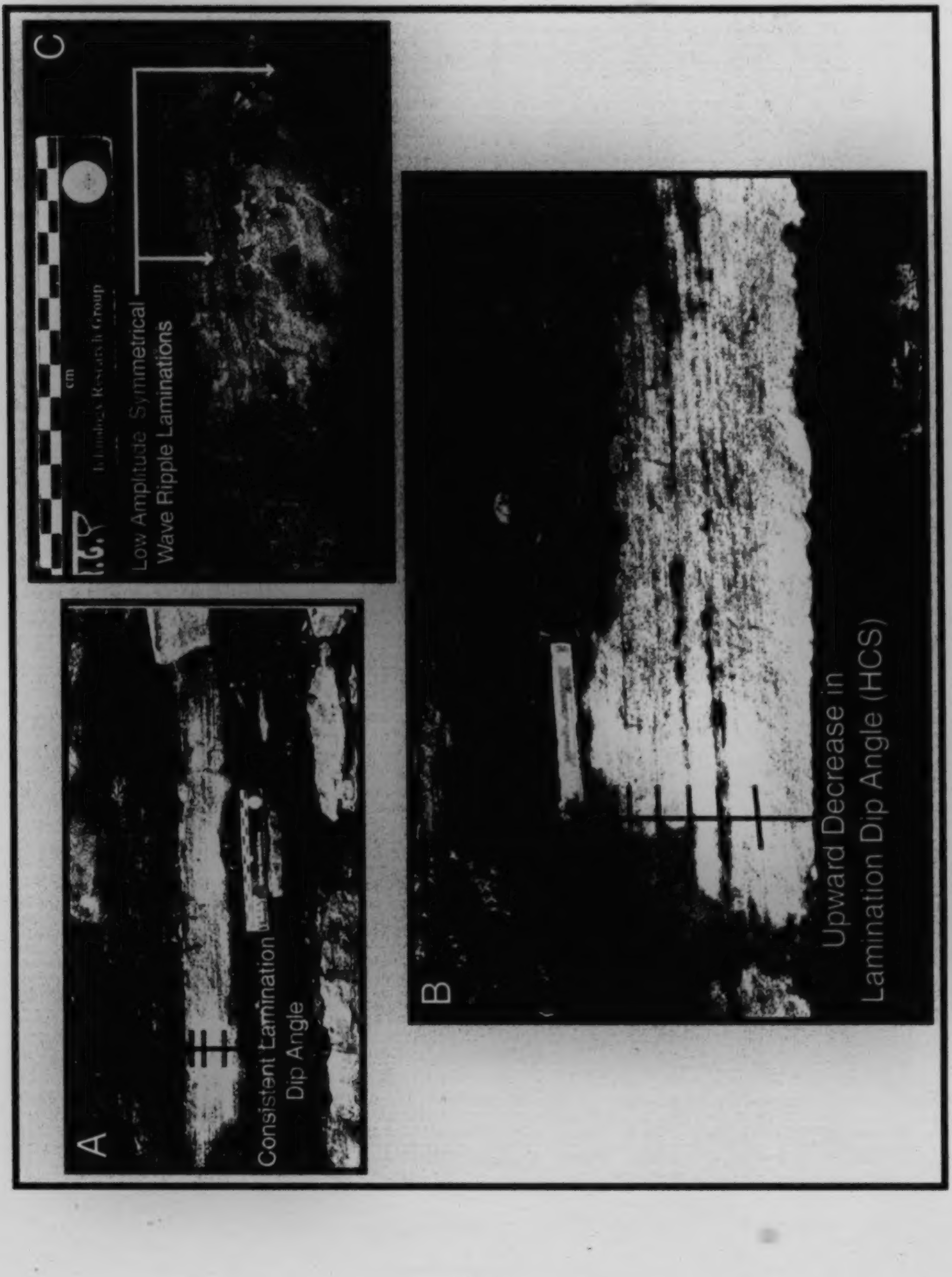

A
Consistent Lamination Dip Angle
B
Upward Decrease in Lamination Dip Angle (HCS)
C
Low Amplitude Symmetrical Wave Ripple Laminations
cm

Figure 2.11 - Three varieties of soft sediment deformation in Facies B (Hulcross) sandstones. A) Flame structure – representative of sediment dewatering, B) Flute casts – indicative of sediment loading and/or scour by strong unidirectional currents, and C) Soft sediment folding – indicative of semi-plastic sediment deformation.

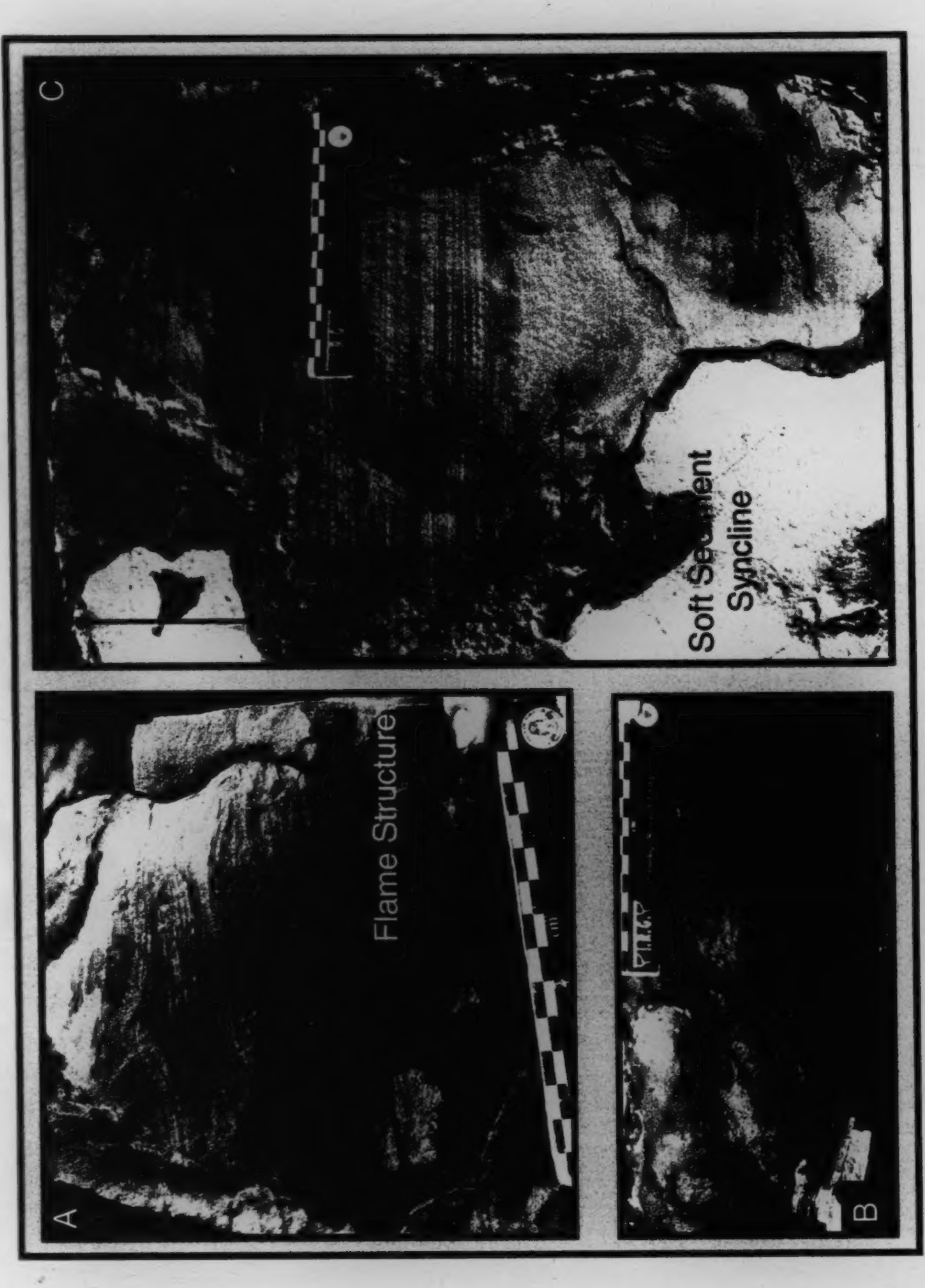

A
Flame Structure
B
C
Soft Sediment Syncline

Figure 2.12 - A) *Teredolites* in petrified and coalified, wood debris from Facies B (Hulcross). Club shaped *Teredolites* (TER) are sand filled (B). Scale is in centimeters.

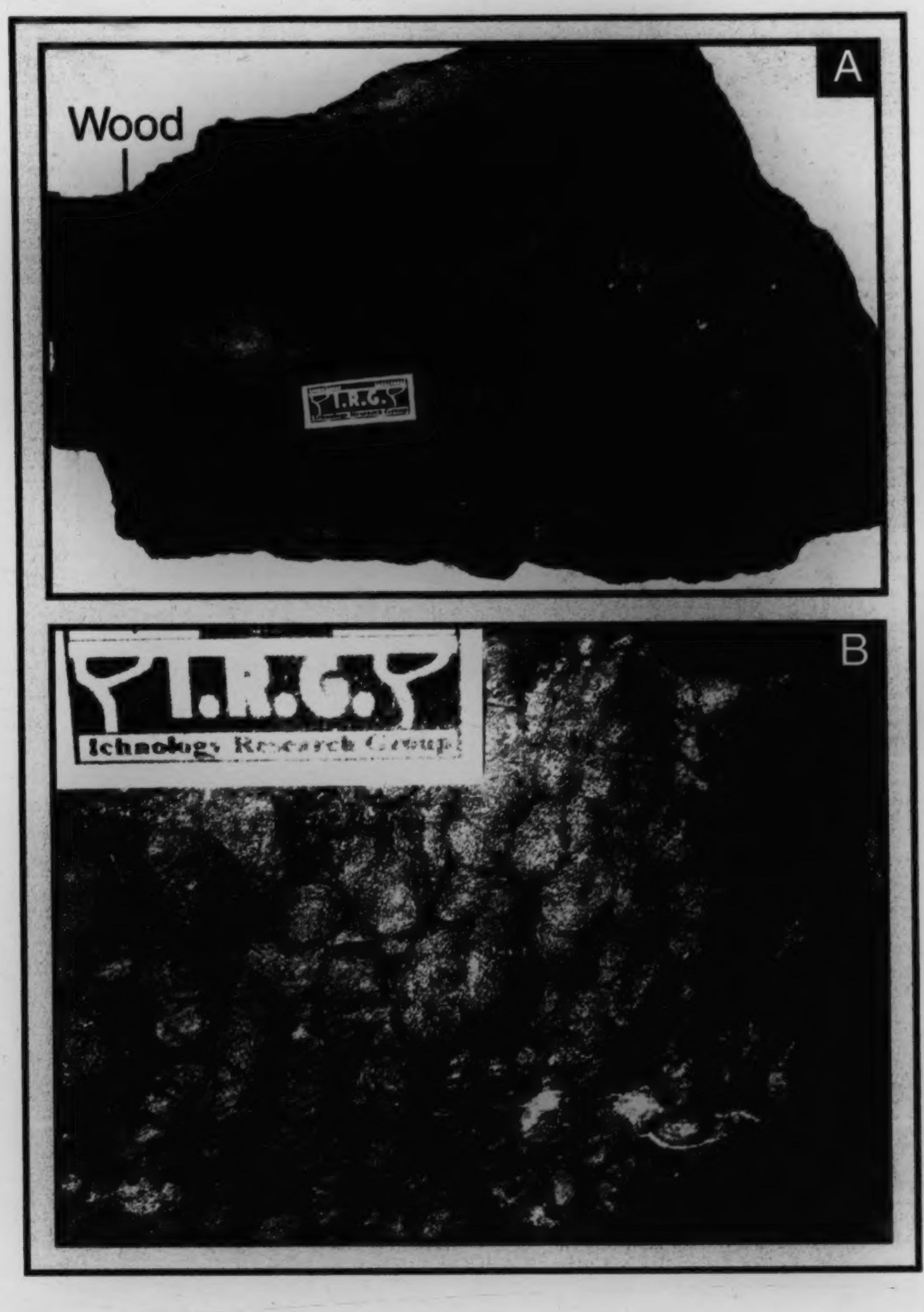

A
Wood
T.R.G.
Ichnology Research Group
B
T.R.G.
Ichnology Research Group

Figure 2.13 - A) Flaggy weathering of hummocky cross-stratified sandstones. Occasionally, an HCS bed will be rippled in the upper portions of the bed (C). Ripples are peaked, symmetrical and straight crested to weakly bifurcating (B – upper bedding plane exposure).

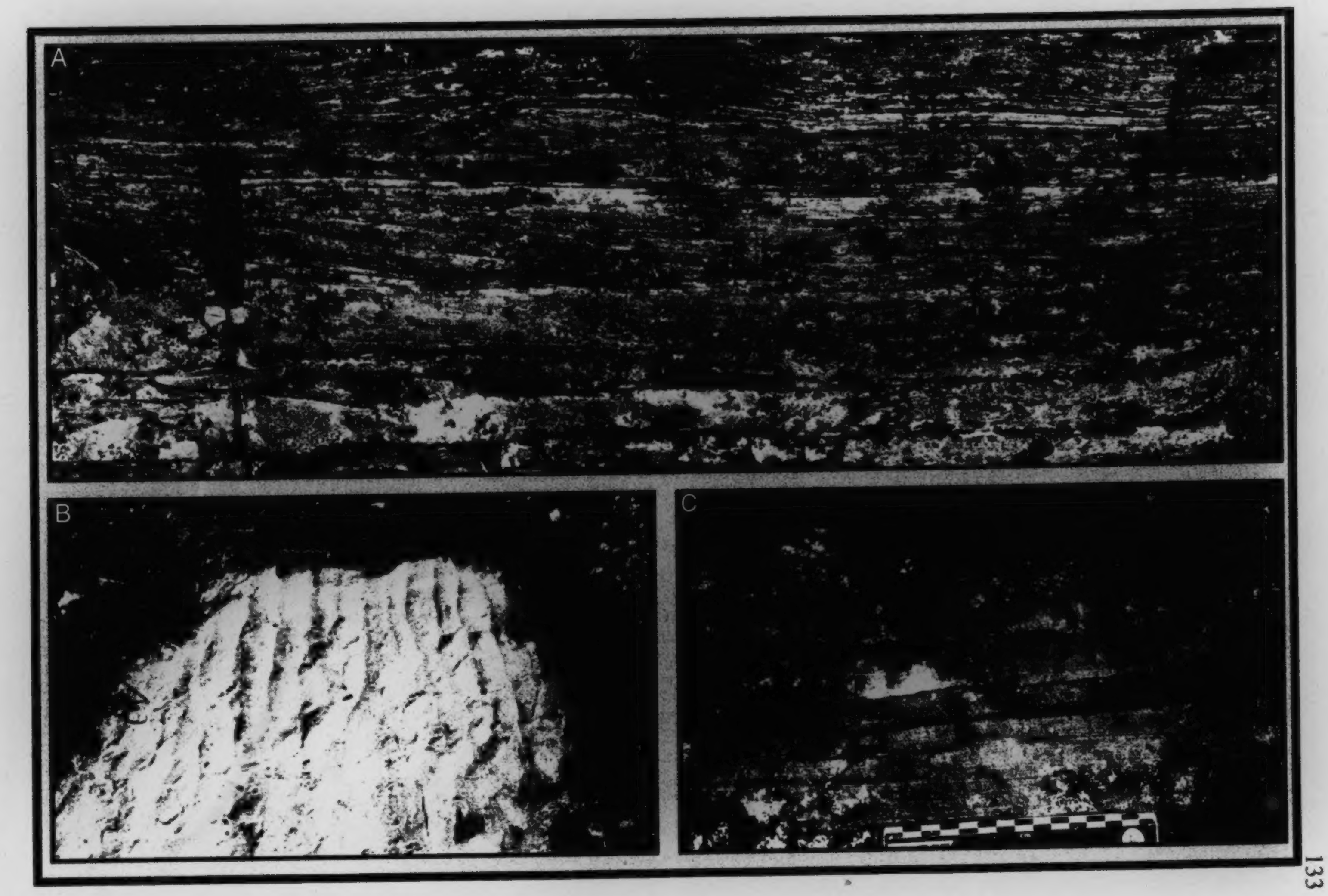
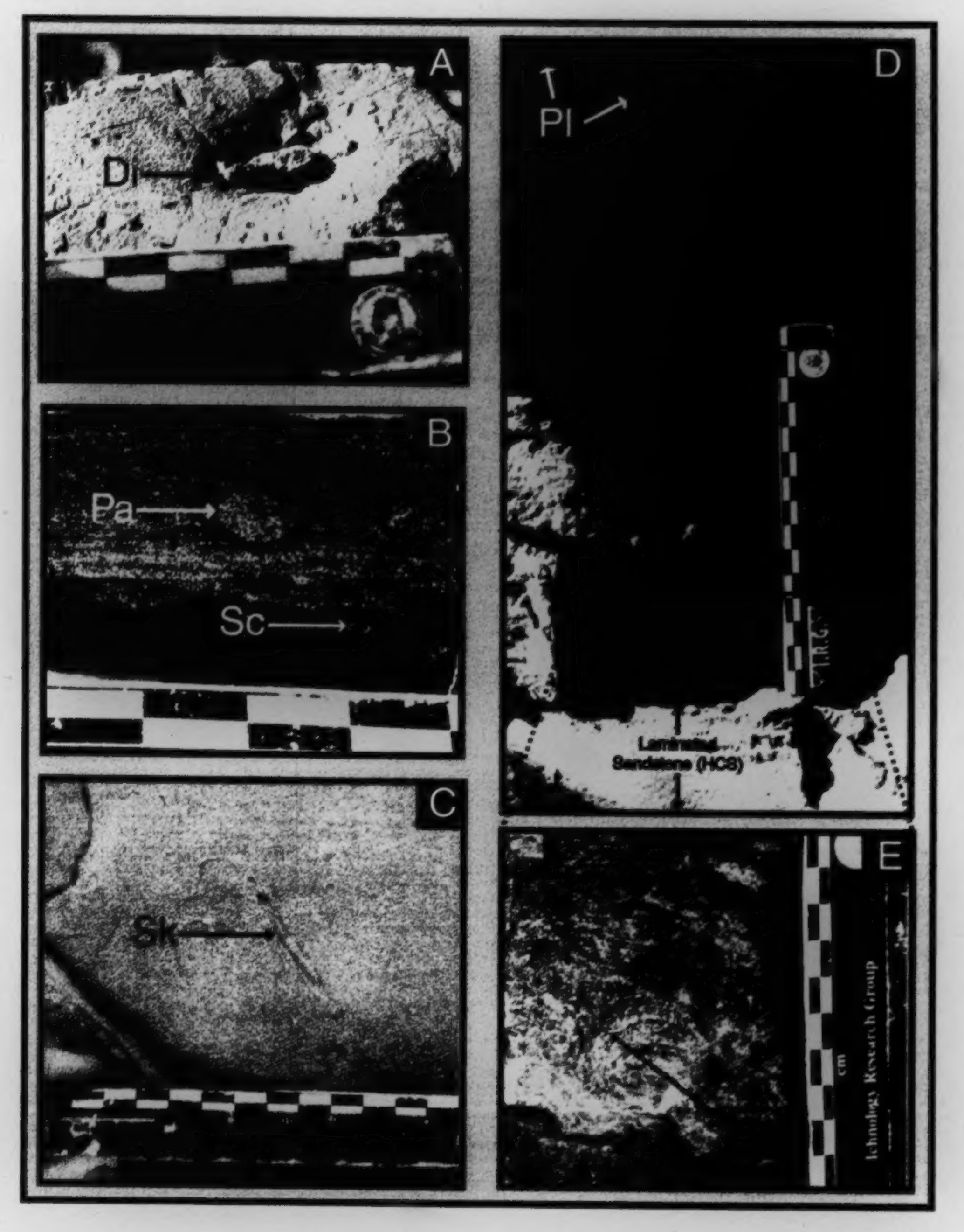

A
B
C

Figure 2.14 - Storm conditions are generally either erosional, or create an environment unfavorable for biologic colonization, and hence, storm deposits have a tendency to be preserved. Opportunistic colonization occurs in immediate waning to post storm conditions. This colonization is characterized by (A) *Diplocraterion* - Di, (B) *Palaeophycus* - Pa, (C) *Skolithos* – Sk, (D) *Planolites* - Pl and (E) Escape Traces -Es. The alternation of periods of sedimentation and biogenic colonization gives the deposit a characteristic laminated to scrambled (lam-scram) fabric (D). Scale is in centimeters.


A
Di
B
Pa
Sc
C
Sk
D
Pl
Laminated Sandstone (HCS)
E
cm
Ichnology Research Group

2.15 - A) *Pseudopulchellia pattoni* collected at Lower Commotion East. B) Ripped-up, mud lined *Rosselia* (Ro) redeposited as a storm lag along the base of an HCS sandstone bed (collected at Dokie Ridge). Both samples are from Facies C (Hulcross).

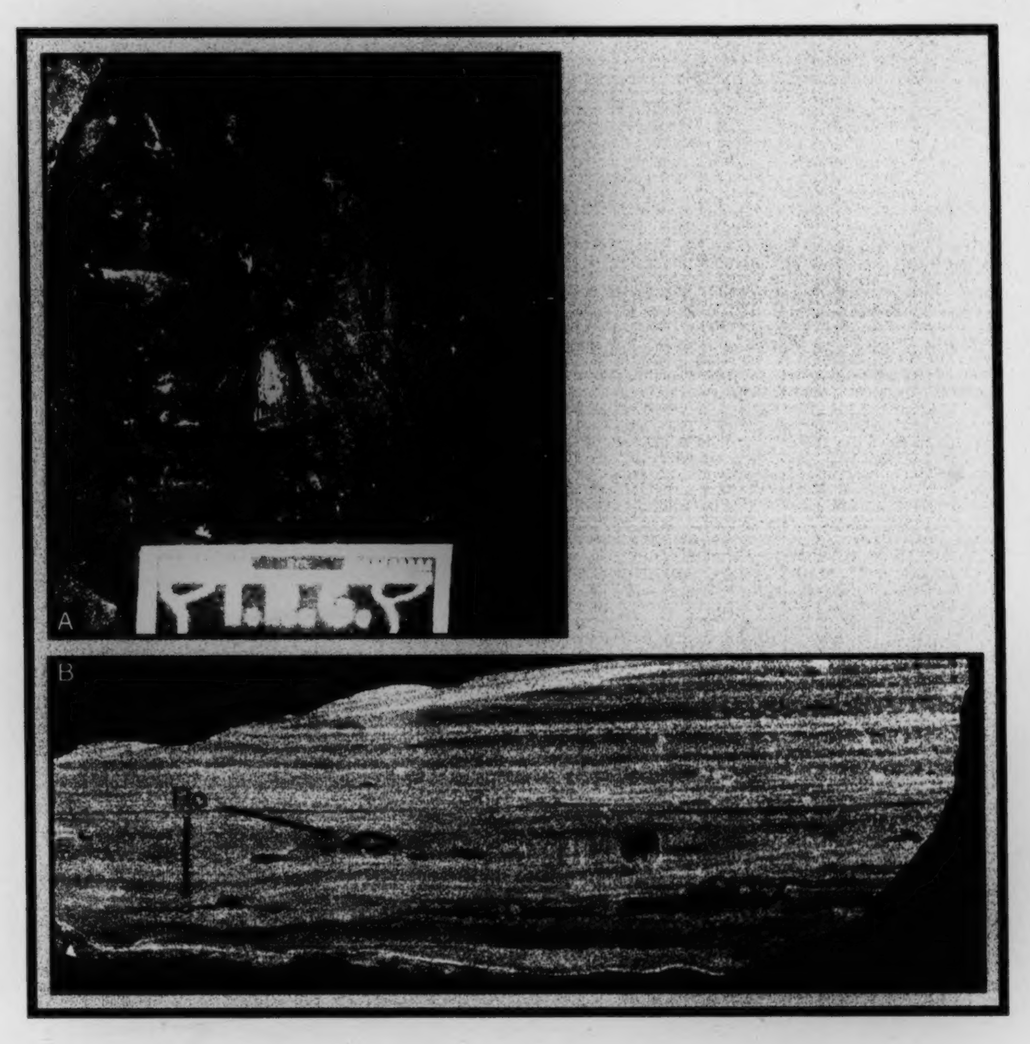

A
B
Po

Figure 2.16 - Facies C Characteristics (Cadotte). A) Pebble filled gutter casts are common in the upper portion of the facies occurrence. The symmetrical nature of this gutter cast suggests a current azimuth into, and out of, the photo. B & C) show characteristics of HCS to SCS beds, onlap and laminations shallowing up bed. Note also the presence of prolific coarse sand and granule to small pebble stringers.

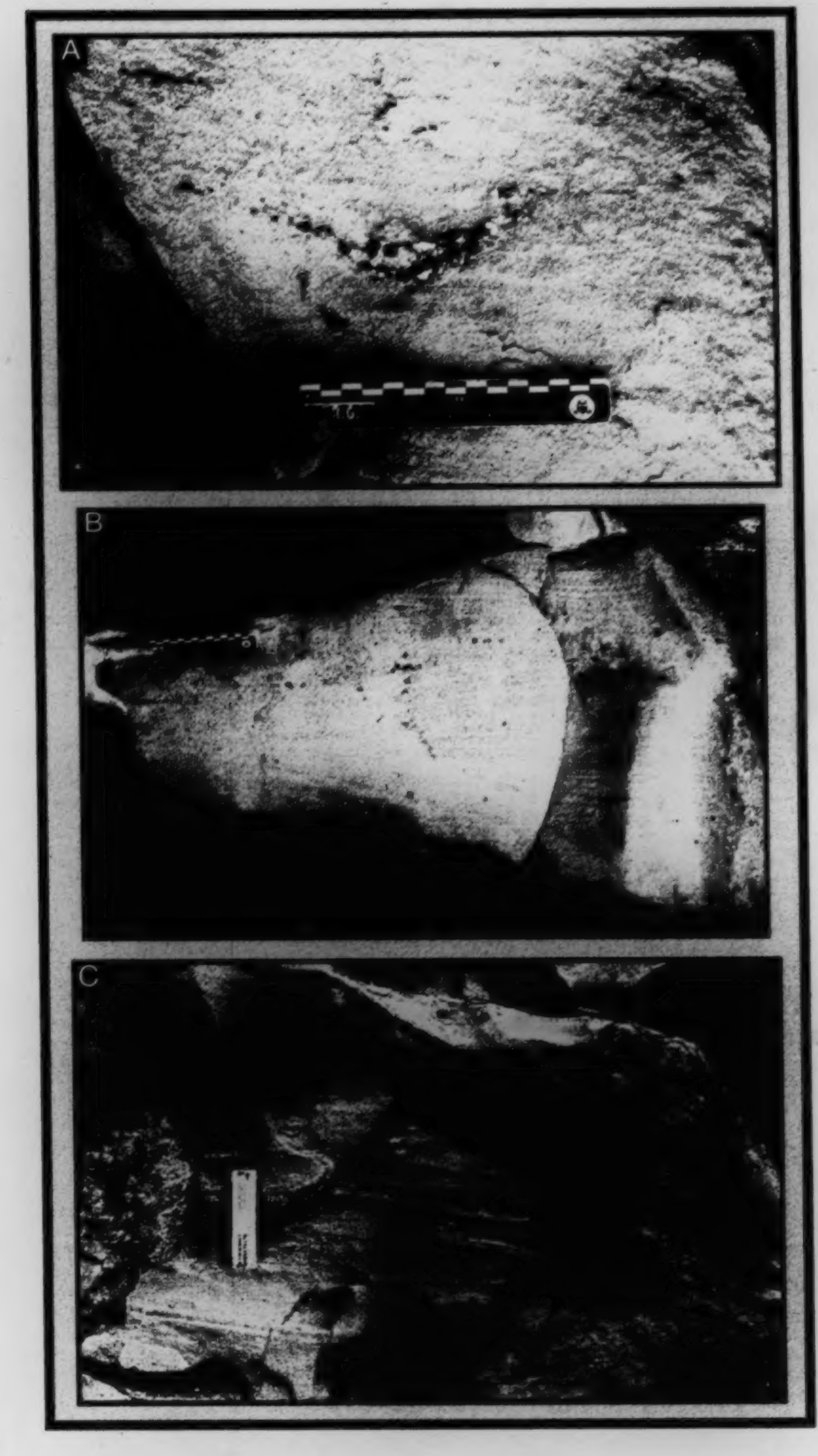

A
B
C

Figure 2.17 - Type 1 Facies C-D Transition (Cadotte). Trough cross stratification providing evidence of a punctuated facies transition between fine, quartz sandstones of Facies C, and the coarse, chert sandstones of Facies D (A, B & C). Facies C/D transition in Canhunter East Pine 7-2-77-24W6, approximately 20 km due east of Commotion Creek, shows an interbedding of underlying fine quartz sand with overlying medium and coarse chert sand (C). Scales are in centimeters.

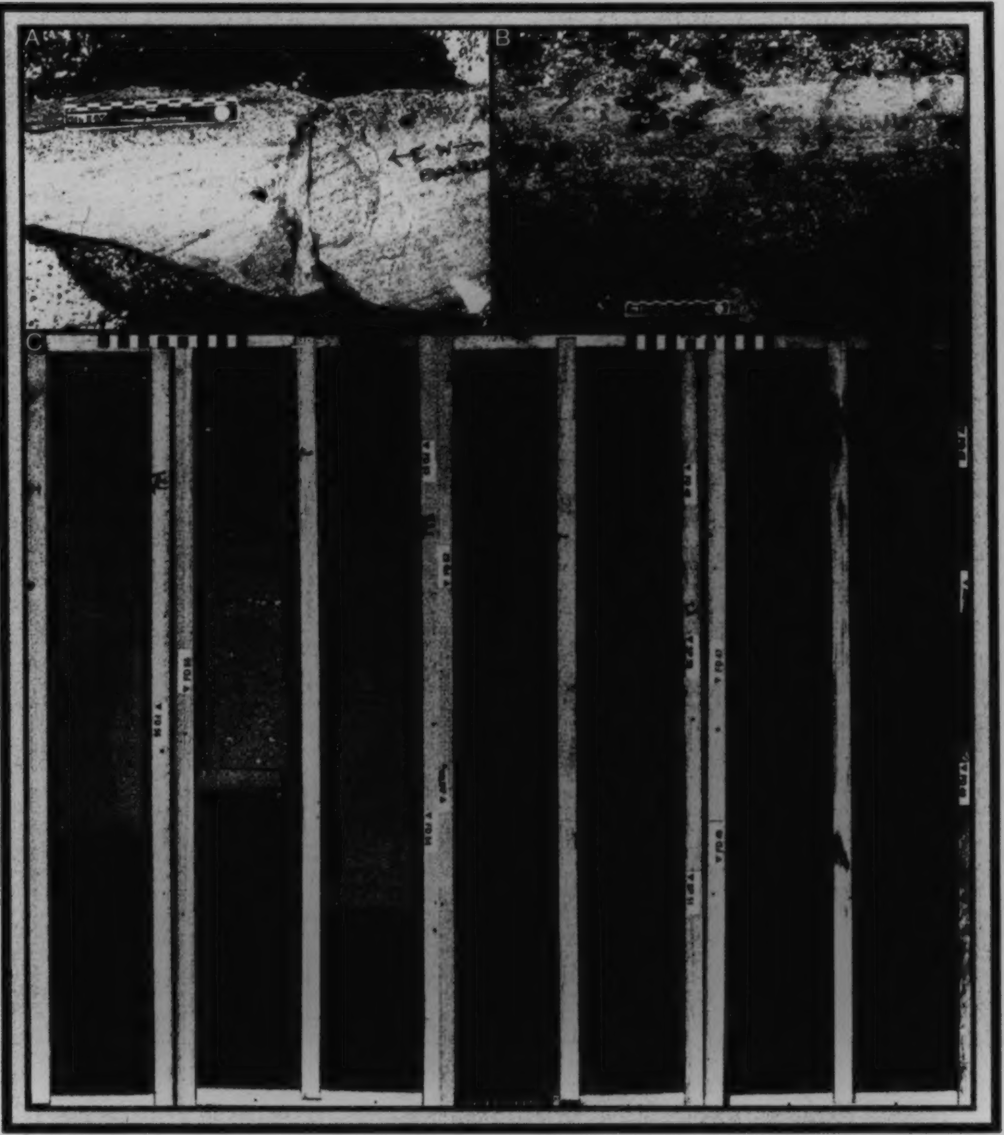

A
B
C

Figure 2.18 - Thin section photos of sediment in: A) Type 1 Transition – mixed fine quartz sand (Qtz) with coarse chert sand (Cht) and B) Type 2 Transition – mixed quartz and chert sand, with increased dark, carbonaceous debris (CD) disseminated throughout the matrix. Both photos are at 10X magnification.

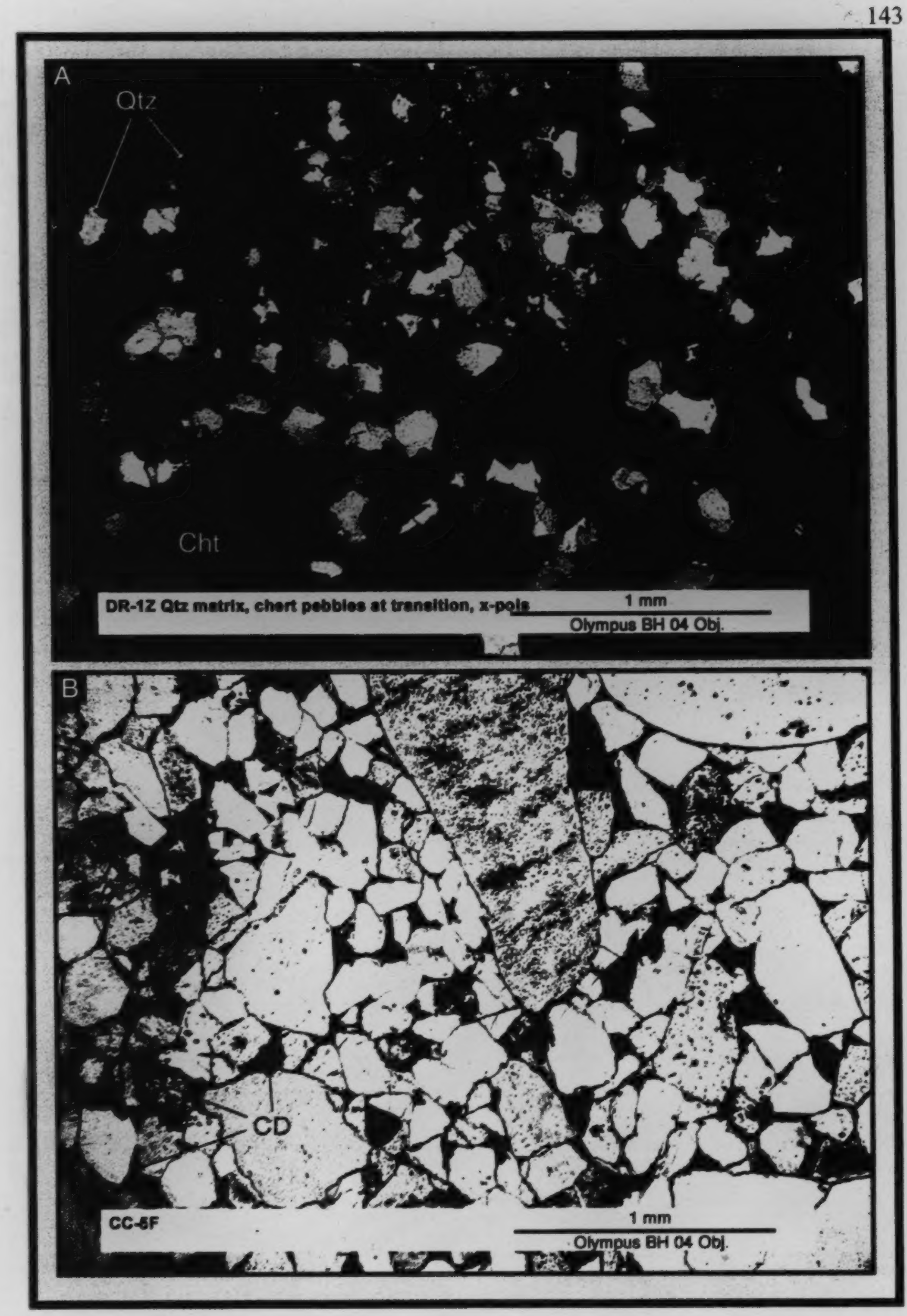

A
Qtz
Cht
DR-1Z Qtz matrix, chert pebbles at transition, x-pols
1 mm
Olympus BH 04 Obj.
B
CD
CC-5F
1 mm
Olympus BH 04 Obj.

Figure 2.19 - Characteristics of Type 2 Contact. A) Wood debris showing preferred long axis orientation. B) Carbonaceous laminations and coal fragments in medium sandstone as well as underlying, basal coarse to very coarse sandstone. C) Normally graded trough fills, from coarse grained basal sandstone to medium grained upper sandstone (followed by a second scour and associated basal, coarse grained sandstone).

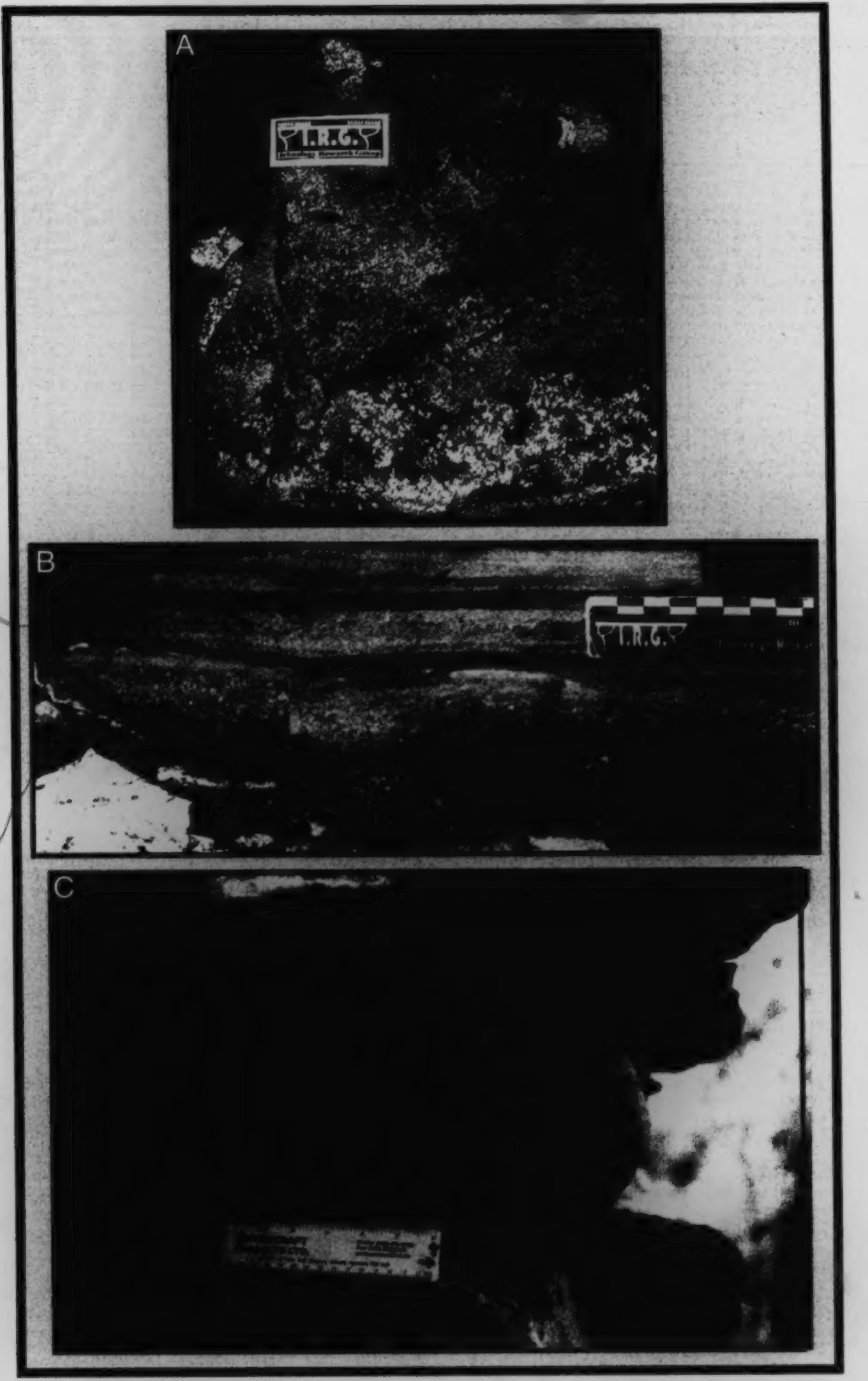

A
I.R.G.
B
I.R.G.
C

Figure 2.20 - *Diplocraterion* (Di) in plan view (A) and cross section (B). The variations in the shape of the surface expression of *Diplocraterion* from a classic barbell appearance to moderately arcuate in nature, indicates that the burrows vary from straight up and down to strongly inclined (A). Note how burrow penetrates down from the top of the high energy medium (M) to coarse (C) grained sandstone, through the basal trough scour and into the underlying, finer grained, laminated sandstone (B). Sample of Cadotte sandstone collected from Commotion West. Scale is in centimeters.

A
Di
I.R.G.
B
I.R.G.
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Figure 2.21 - Wave ripples at Type 2 Contact present between Facies' C and D (Cadotte) at Commotion West. A) Symmetrical wave ripples (WR) in medium sandstone and underlying, associated, rip channel scours (CS). B) Weakly aggrading, symmetrical ripple in silstone. Both ripple examples have crest azimuths that trend between 337.5 and 22.5 degrees. Scale is in centimeters.

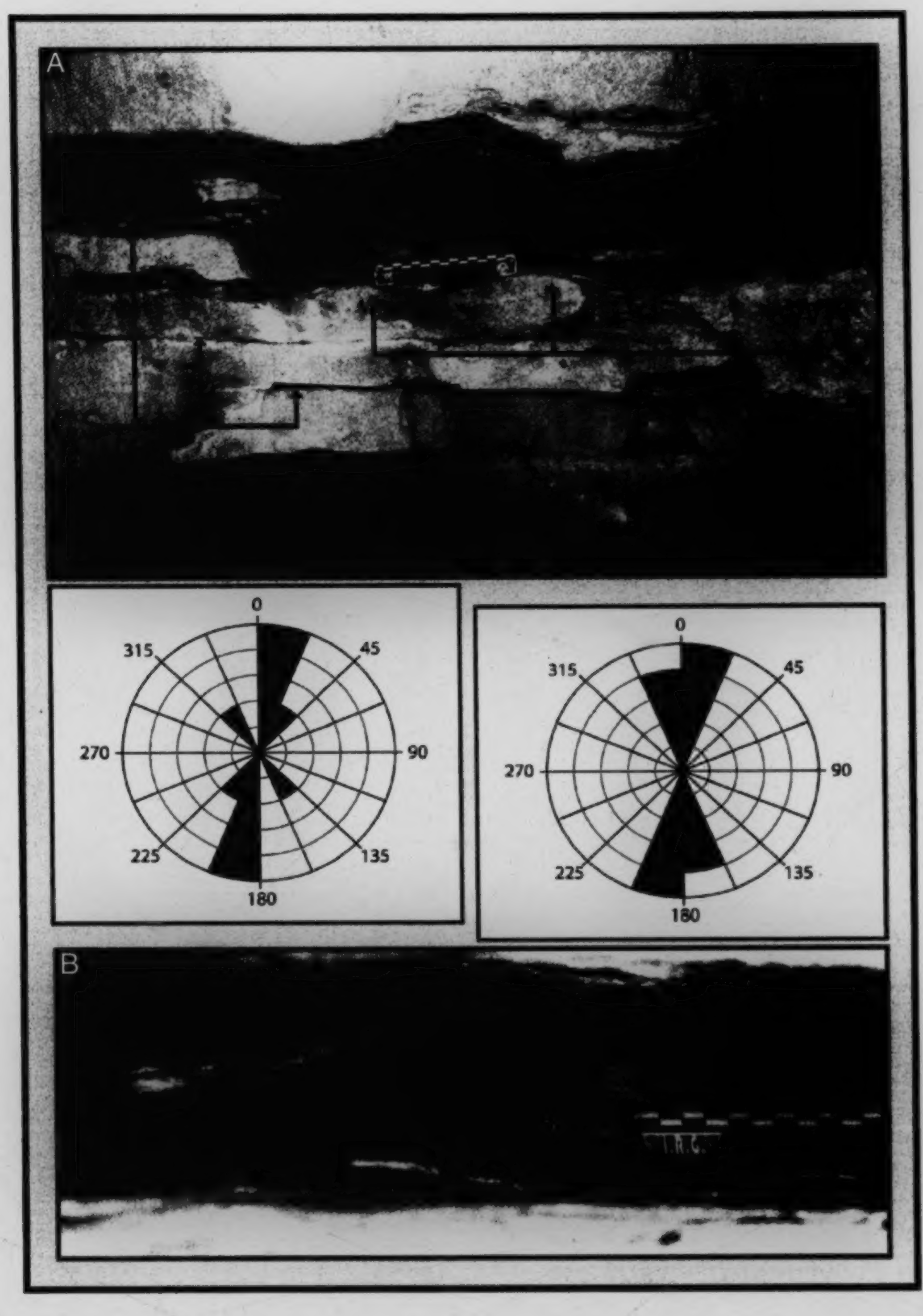

A
0
45
90
135
180
225
270
315
0
45
90
135
180
225
270
315
B

Figure 2.22 - Facies C to E sedimentological profile (Cadotte). A) Core photos and associated lithologic description from Drillhole #1. Strip log and core photos are color coded by facies (C - yellow, Type 2 Transition Zone - blue, D - red, and E - orange). Boxed intervals on the core photos correspond to blow-ups at the right of the figure. Note the interfingering relationship between Facies D and E. B) Blow up of a coarse sand filled gutter cast in Facies C. C) Type 2 Transition characterized by truncated ripple laminations (RL) overlain by a scour surface (SC) and associated coarse sandstone bed. The coarse sandstone bed is abruptly overlain by a carbonaceous laminated (CL) medium-grained sandstone. Continuing up core, repeated scour surfaces are present until medium and finer sandstones are finally eliminated from the section. D) Foreset lamination (FS) in trough cross-bedded Facies D. E) Poorly sorted, coarse grained, polymodal nature of Facies E. Scales are in centimeters.

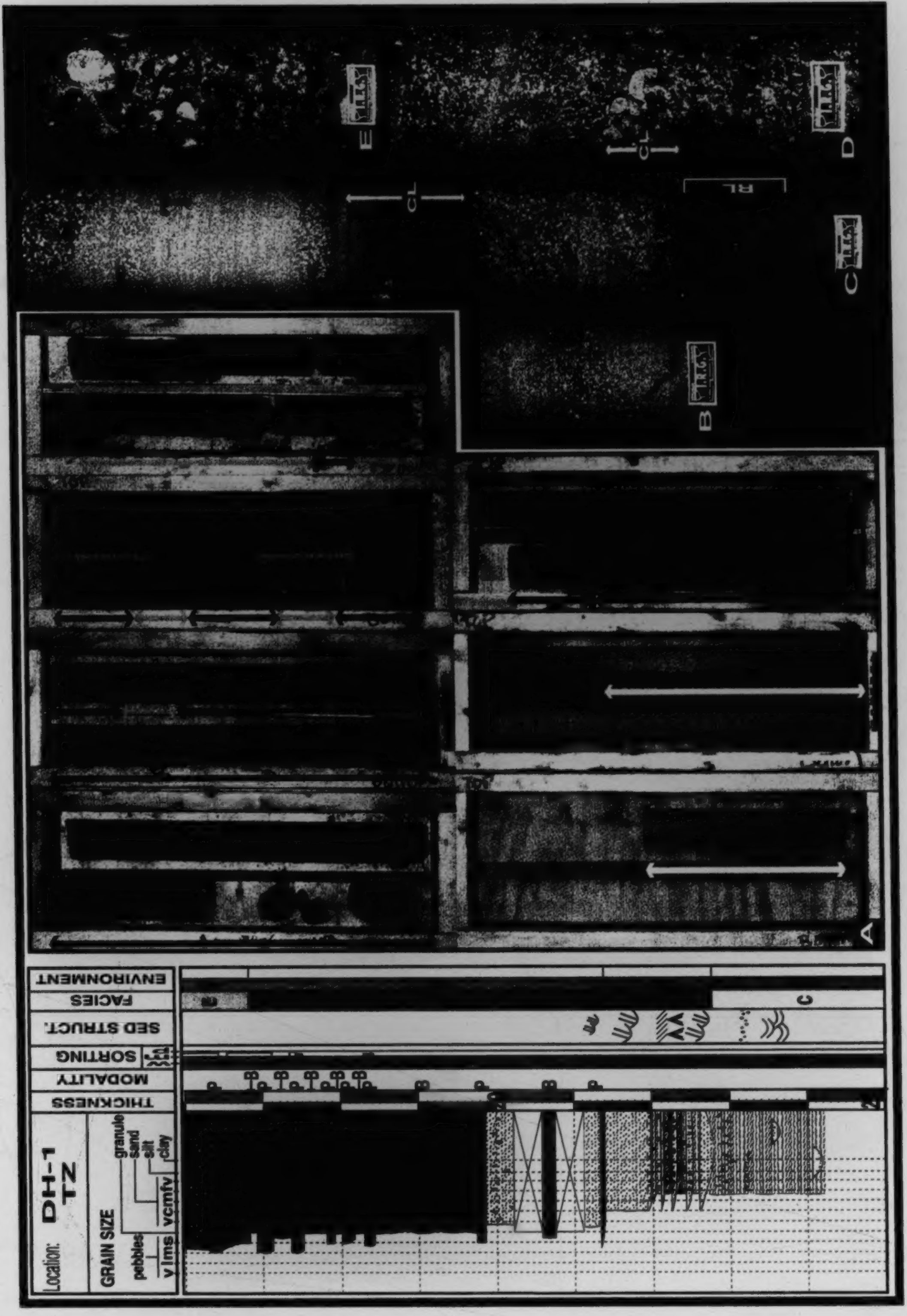

Location: DH-1 TZ
GRAIN SIZE
pebbles
granule
sand
silt
clay
v l m s
vcmfv
THICKNESS
MODALITY
SORTING
SED STRUCT.
FACIES
ENVIRONMENT
c
A
B
C
D
E
CL
CL
RL

Figure 2.23 - A) Outcrop profile of Cadotte from Commotion Creek illustrating weathering profile and outcrop nature of Facies C through F. B) Steeply dipping north to northeast oriented upper shoreface clinoforms (Facies E). C) Onlapping appearance of storm generated bars that have migrated into, and welded onto, the upper shoreface (clipboard in the foreground for scale).

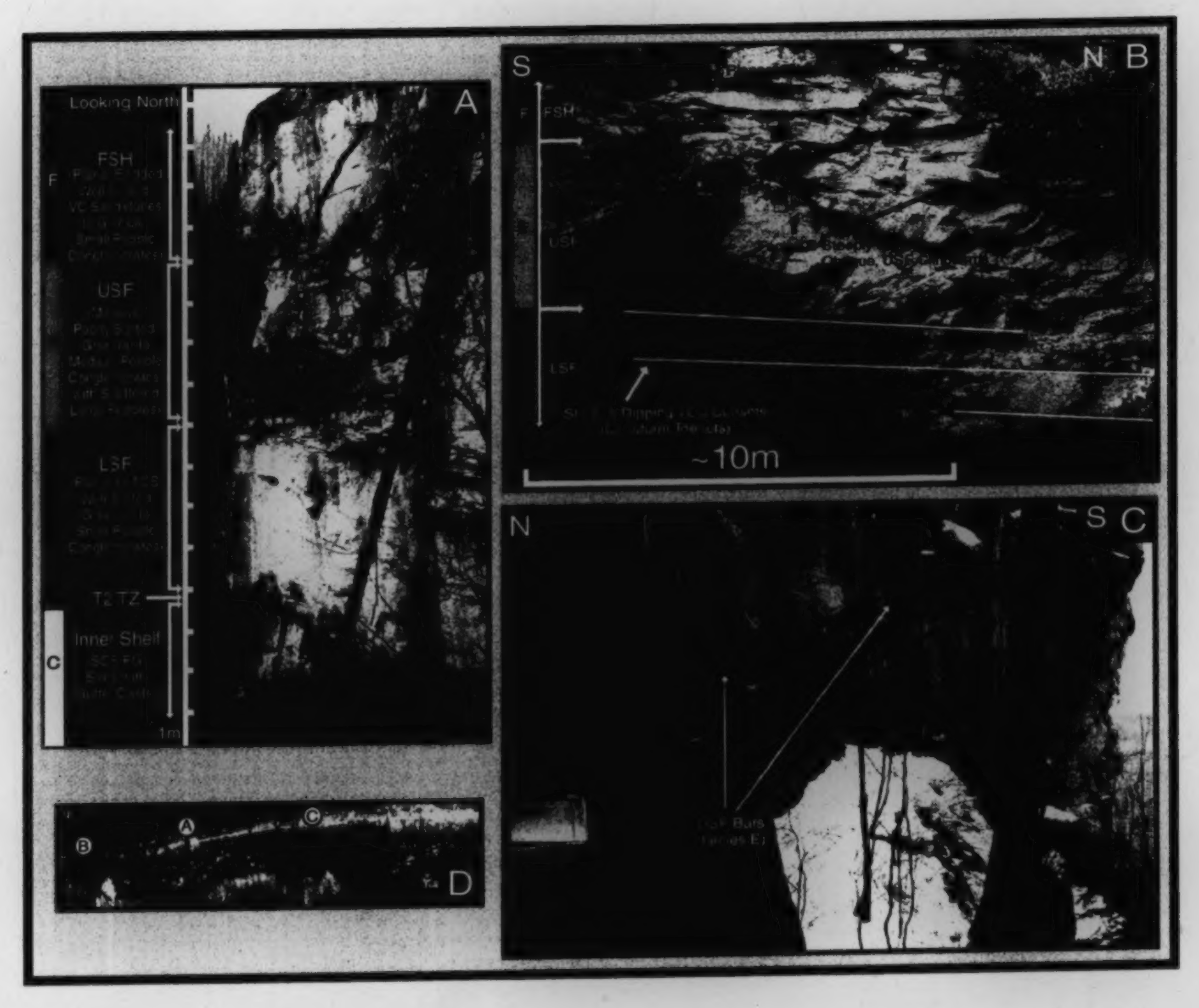

A
Looking North
FSH
F
VC Sandstones
Small Pebble
USF
Poorly Sorted
LSF
T2 TZ
Inner Shelf
C
1m
S
N B
FSH
USF
LSF
~10m
N
S C
Bars
D
B
A
C

Figure 2.24 - Well developed and preserved, trough cross stratification (TCS) in facies D of Cadotte (A & C). B) Sediment is moderately to well sorted and shows evidence of possible foreset laminations (yellow dashed lines). Photos are from; A - Commotion East, B - Drillhole #1 core (scale in centimeters), C – Commotion Creek.

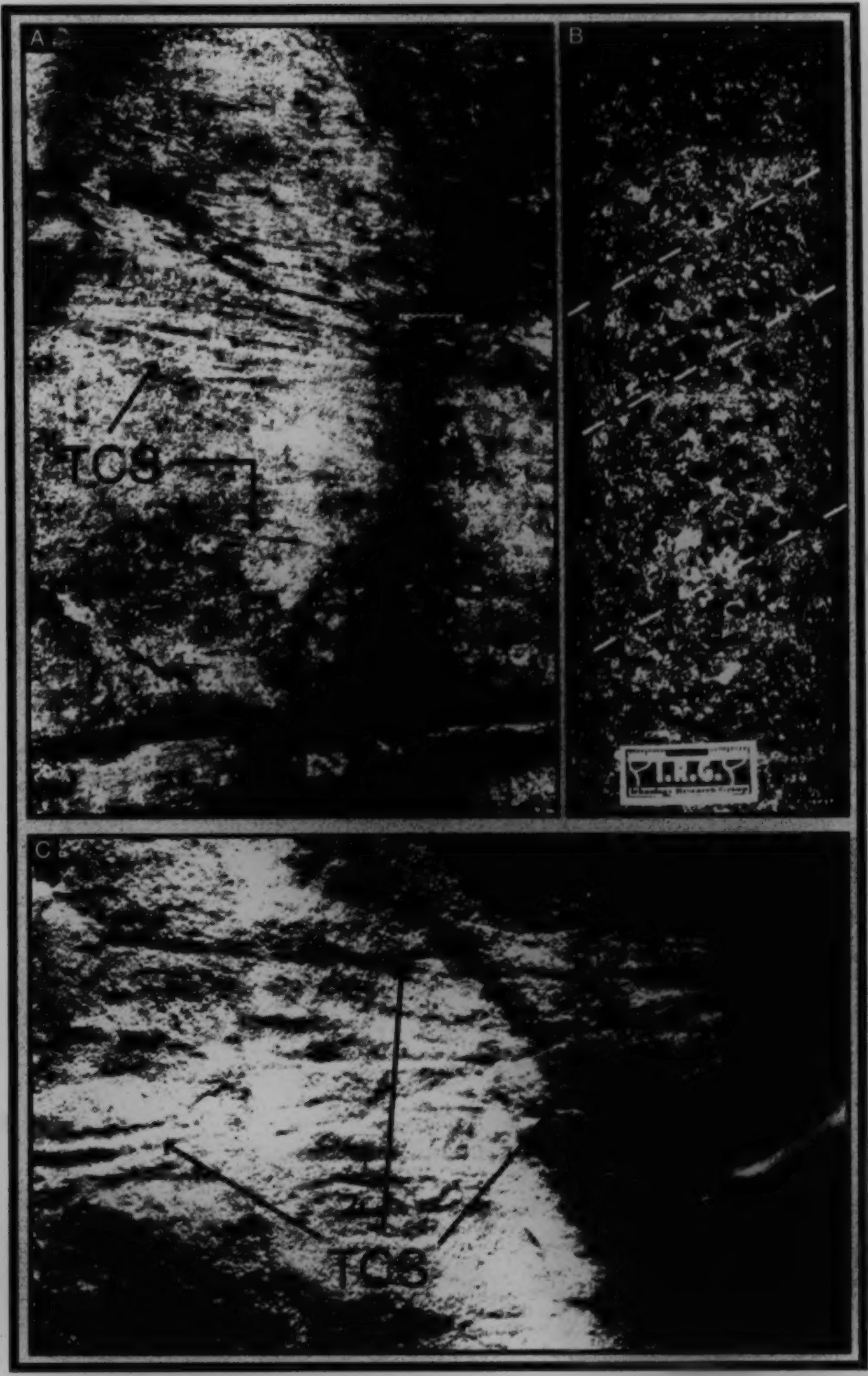

A
TCS
B
I.R.G.
C
TCS

Figure 2.25 - Large, shallow, rip channel trough scours of Facies D from Commotion Creek (Cadotte). The occurrence of these structures is laterally discontinuous (< ~20m). Ice axe for scale.

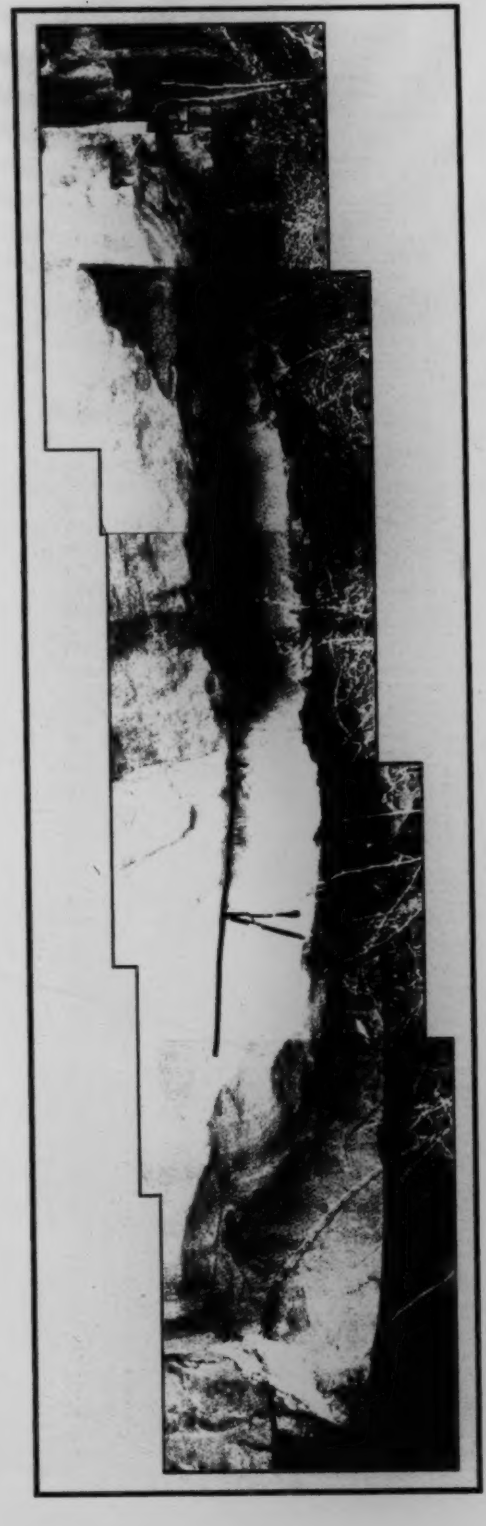


Figure 2.26 - Facies E bedding styles (Cadotte). A) Coarse, highly polymodal, poorly sorted nature of Facies E conglomerate. B & C) Rip channel scours in Facies E commonly re-scour earlier scours. D) Large scale Facies E inclined clinoforms. A through C are from Commotion Creek, D is from Commotion West.

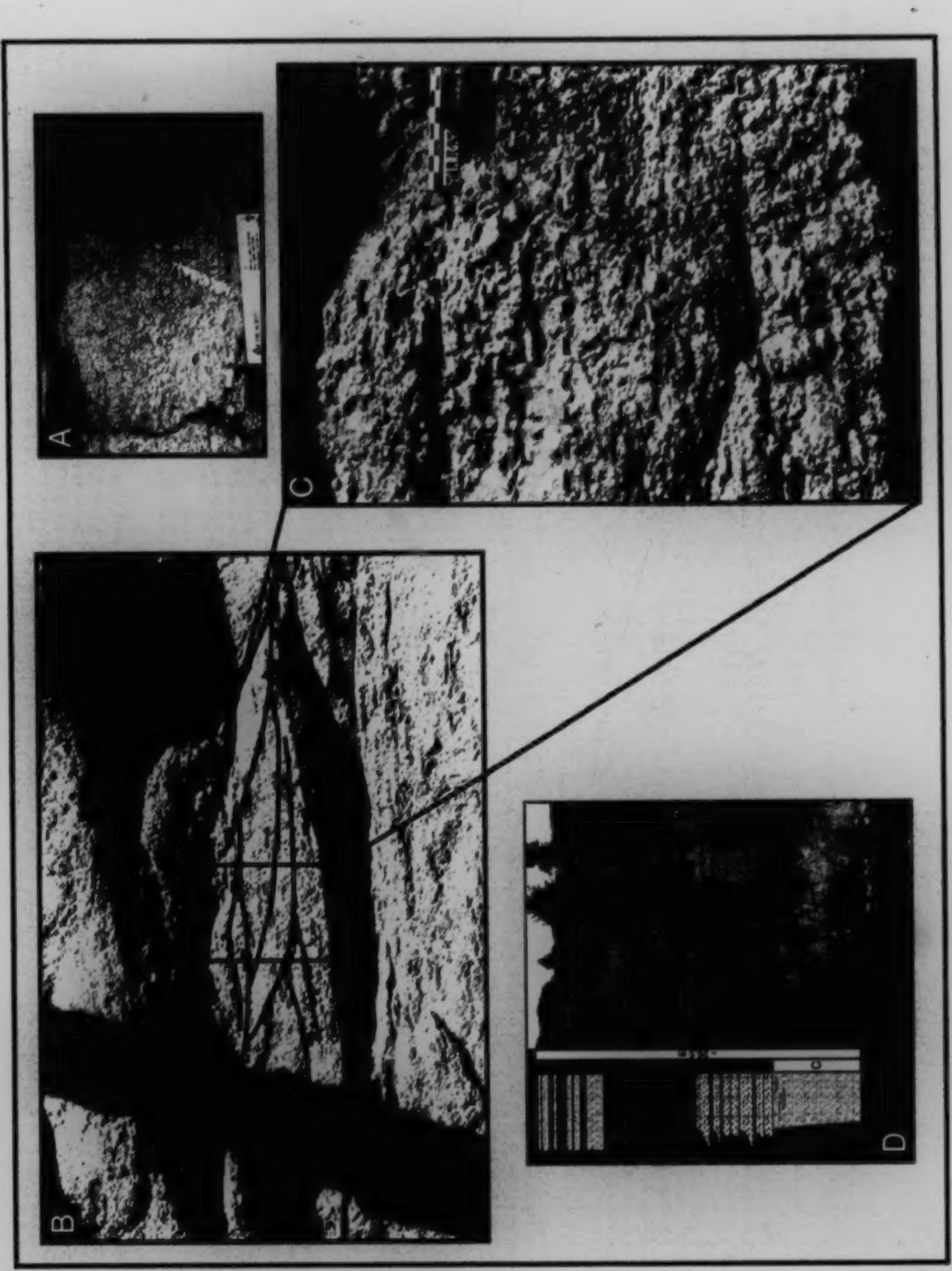

A
B
C
D

Figure 2.27 - Facies F upper and lower transitions (Cadotte). A) Coarse nature of the Plunge Step, or Beach Toe (BT) contrasts strongly with the well sorted, finer grained, low angle to flat-bedded nature of Facies F. Note the Facies F lower transition is sharp and defined by the appearance of the first well, sorted, finer grained, low angle to plane bed (marked in red). B) Color contrast between lower (LFS) and upper foreshore(UFS). The variation in color is due to increased comminuted carbonaceous debris disseminated throughout the matrix of the UFS. C) Facies F sharp, upper transition with Facies G. The transition is marked by a dramatic change in sorting, grain size and modality between the upper foreshore (UFS) and the backshore (BS). Photos are from Drillhole #1 core. Scale is in centimeters.

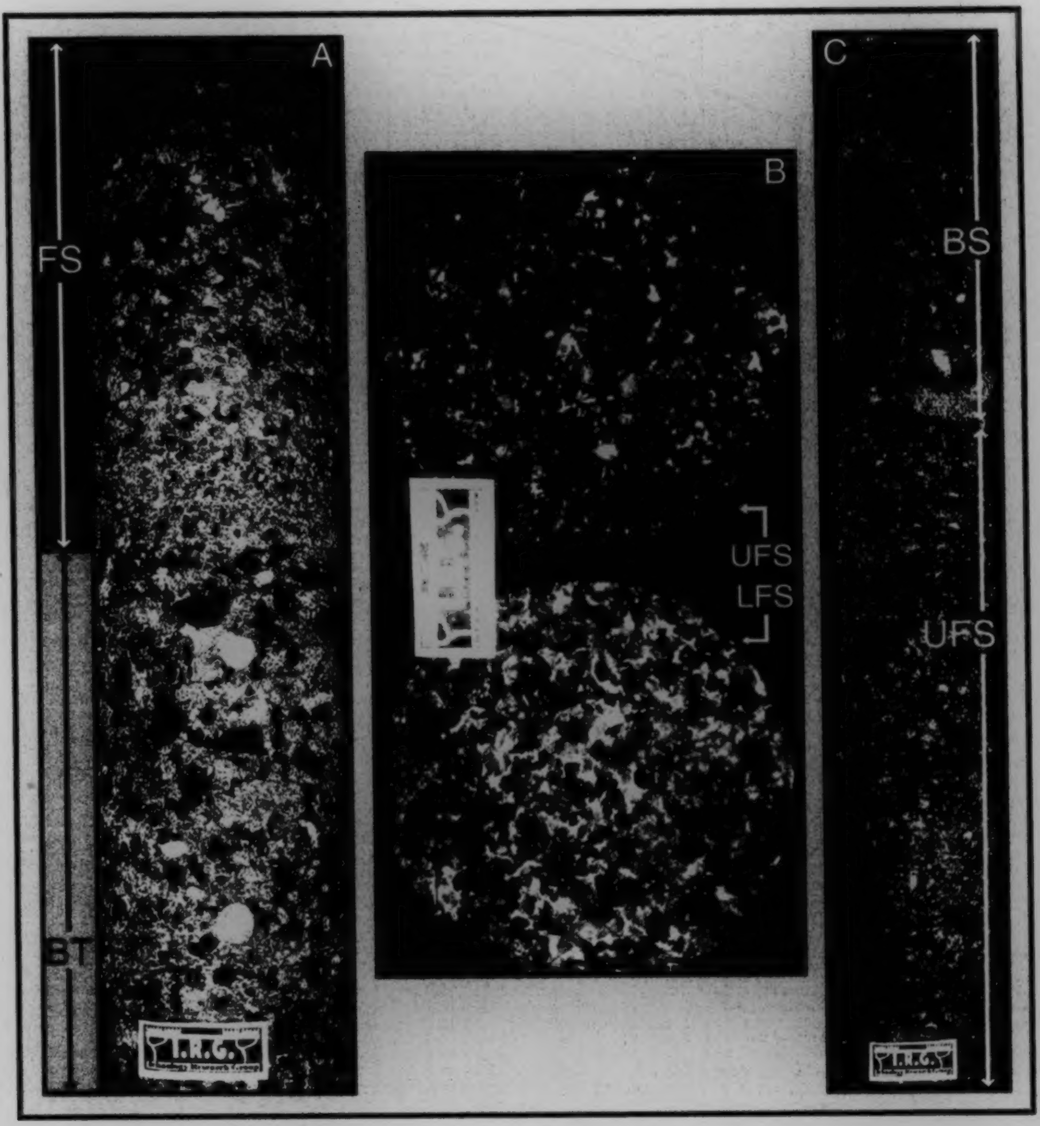

A
FS
BT
B
UFS
LFS
C
BS
UFS
I.R.G.
I.R.G.

Figure 2.28 - Facies F (foreshore) bedding style evident in the Cadotte. A) Low angle to flat beds dominate the facies occurrence. B) Sediment is well to very well sorted, uni to bimodal and ranges from very coarse sandstone to matrix supported, small pebble conglomerate. Bedding contacts (BC) within facies F are often recognizable as fluctuations in grain size. C) Pebble imbrication in small to medium pebble matrix supported conglomerate plane bed (rose diagram shows a preferential clast long axis dip oriented between 22.5 and 45 degrees). A and C are from Commotion Creek while B is from Drillhole #1 core. All scales are in centimeters.

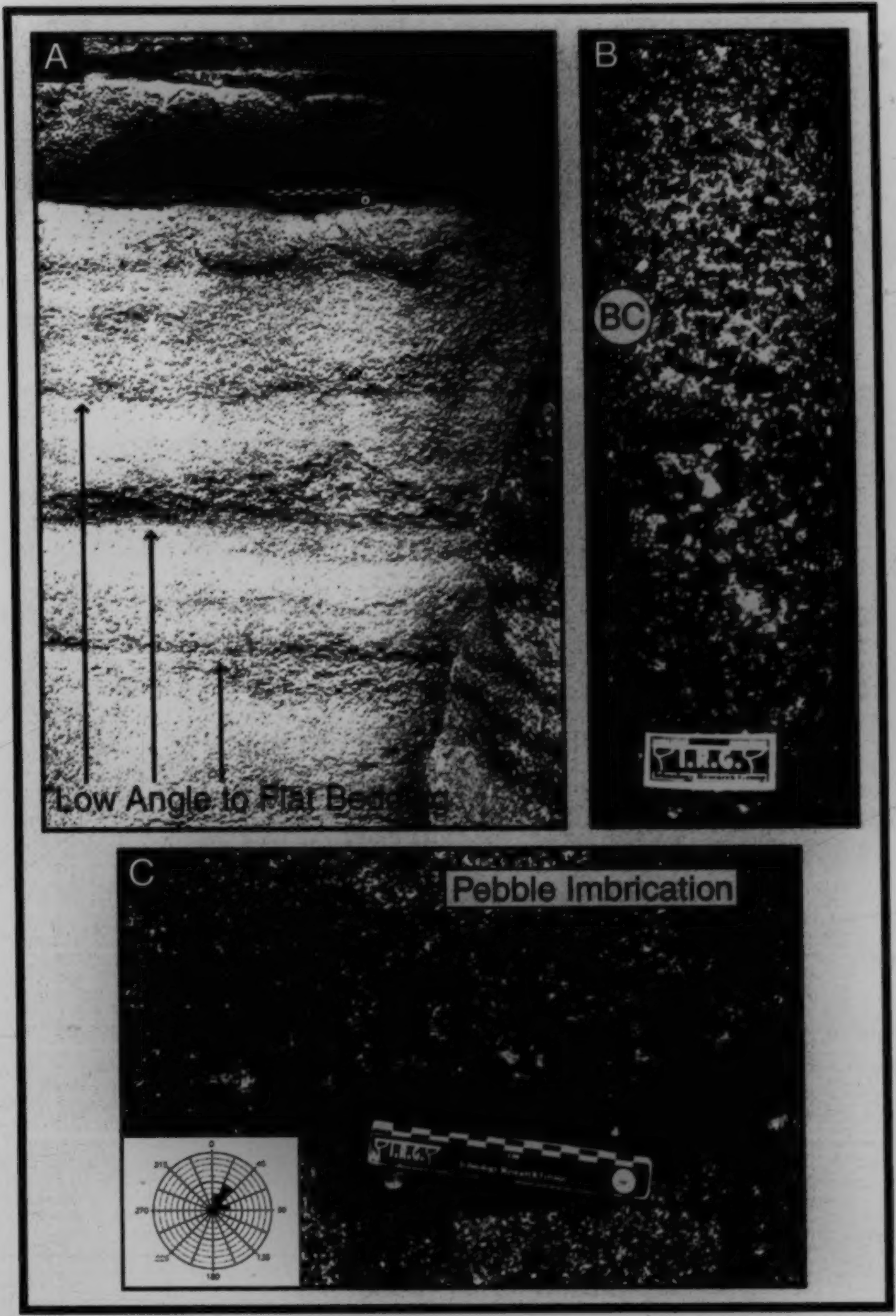

A
Low Angle to Flat Bedding
B
BC
C
Pebble Imbrication
0
45
90
135
180
225
270
315

Figure 2.29 - Facies G characteristics. A) Cyclicity in Facies G. Facies G shows two individual normally graded bed sets (red arrows), characterized by high concentrations of carbonaceous debris. Lower unit is coarser grained than the upper. Note abruptness of upper Facies G contact. B) Alluviated clay (AC) within the matrix of Facies G. C) Authigenic kaolinite disseminated throughout the matrix of backshore conglomerate.

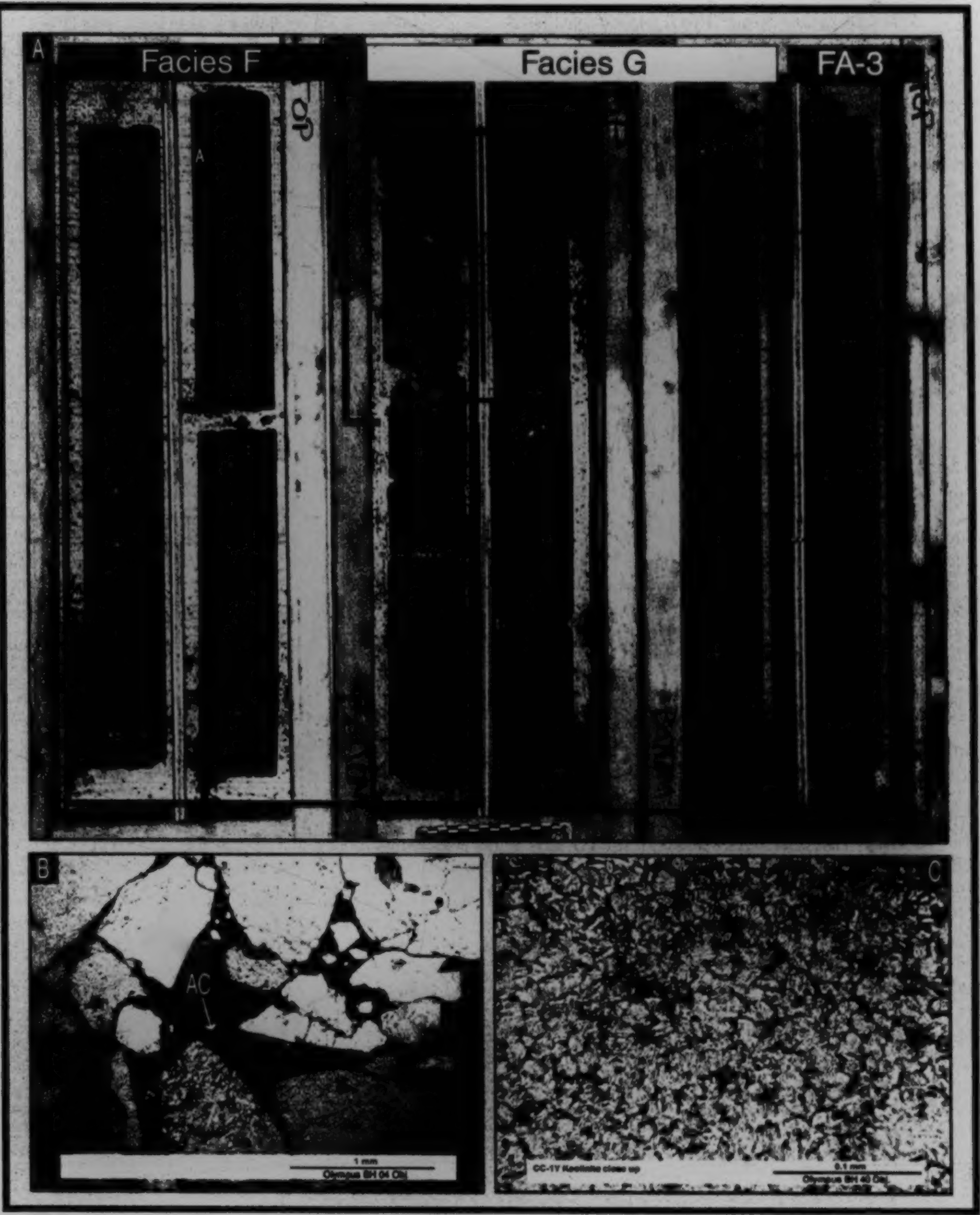

A
Facies F
Facies G
FA-3
top
top
B
AC
1 mm
Olympus BH 04 Obj
C
CC-1Y Kaolinite close up
0.1 mm
Olympus BH 40 Obj

Figure 2.30 - Facies Association 2/Facies Association 3 contacts (Cadotte). A) Shows irregular upper FA 2 bedding plane surface interpreted to represent preserved gravel dunes. B) Sharp transition from Facies G sandstones to FA 3 shale. C) Prominent nature of Facies G, compared with recessive nature of overlying FA 3. A is from Dokie Ridge, B is from Drillhole #1 core and C is from Commotion Creek.

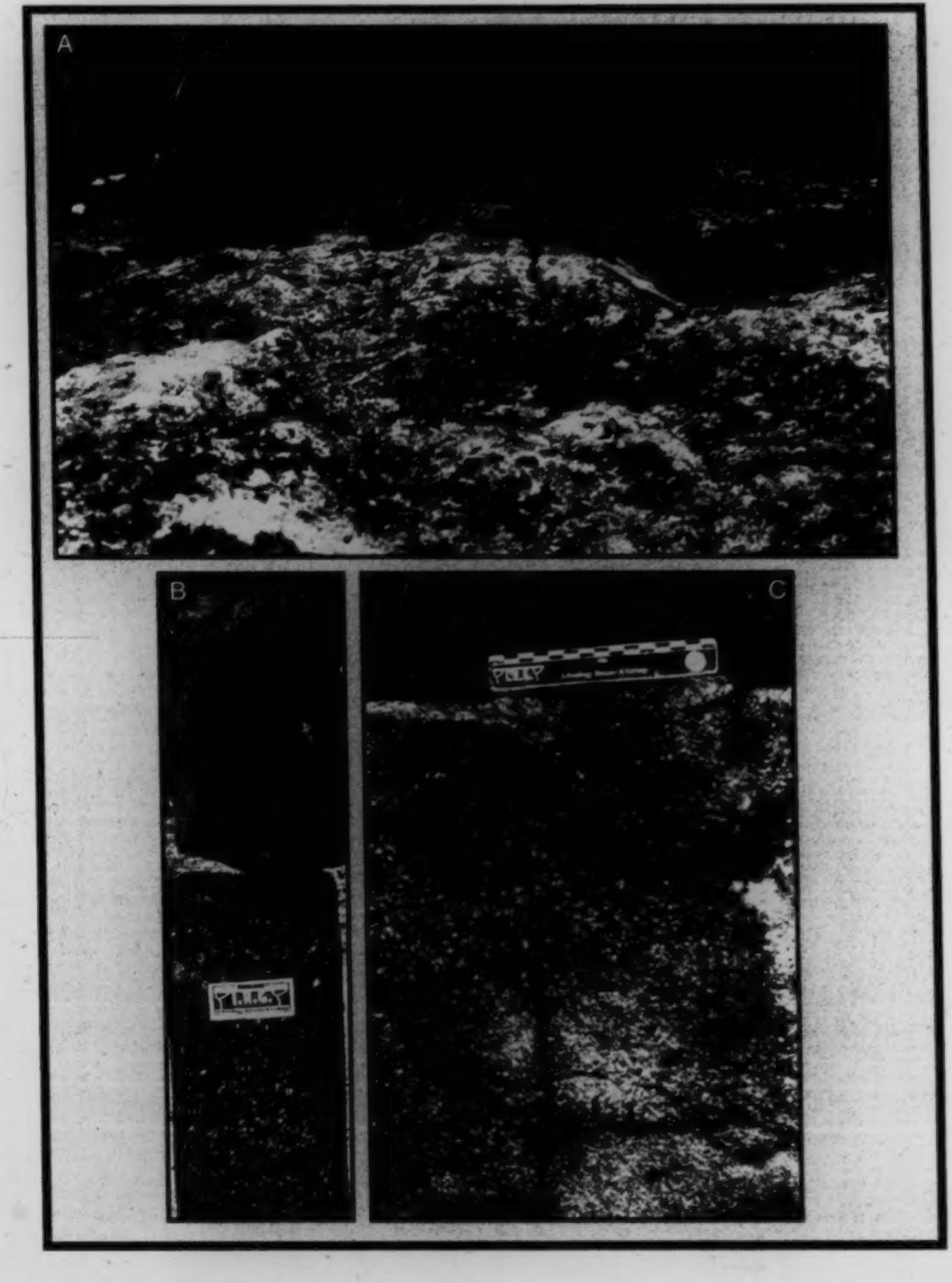

A
B
C

Figure 2.31 - Facies Association 3 (Walton Creek) litho-units from upper bench at Commotion West. A) Vertical grain size profile super-imposed on outcrop photo showing stratigraphic location and characteristics of L1, L2 and L3. B) Close up of L2-L3 flooding/transgressive surface. Note the relatively abrupt nature of the L2-L3 contact. Photos are from the outcrop bench on top of Commotion West. Hammer for scale in A.

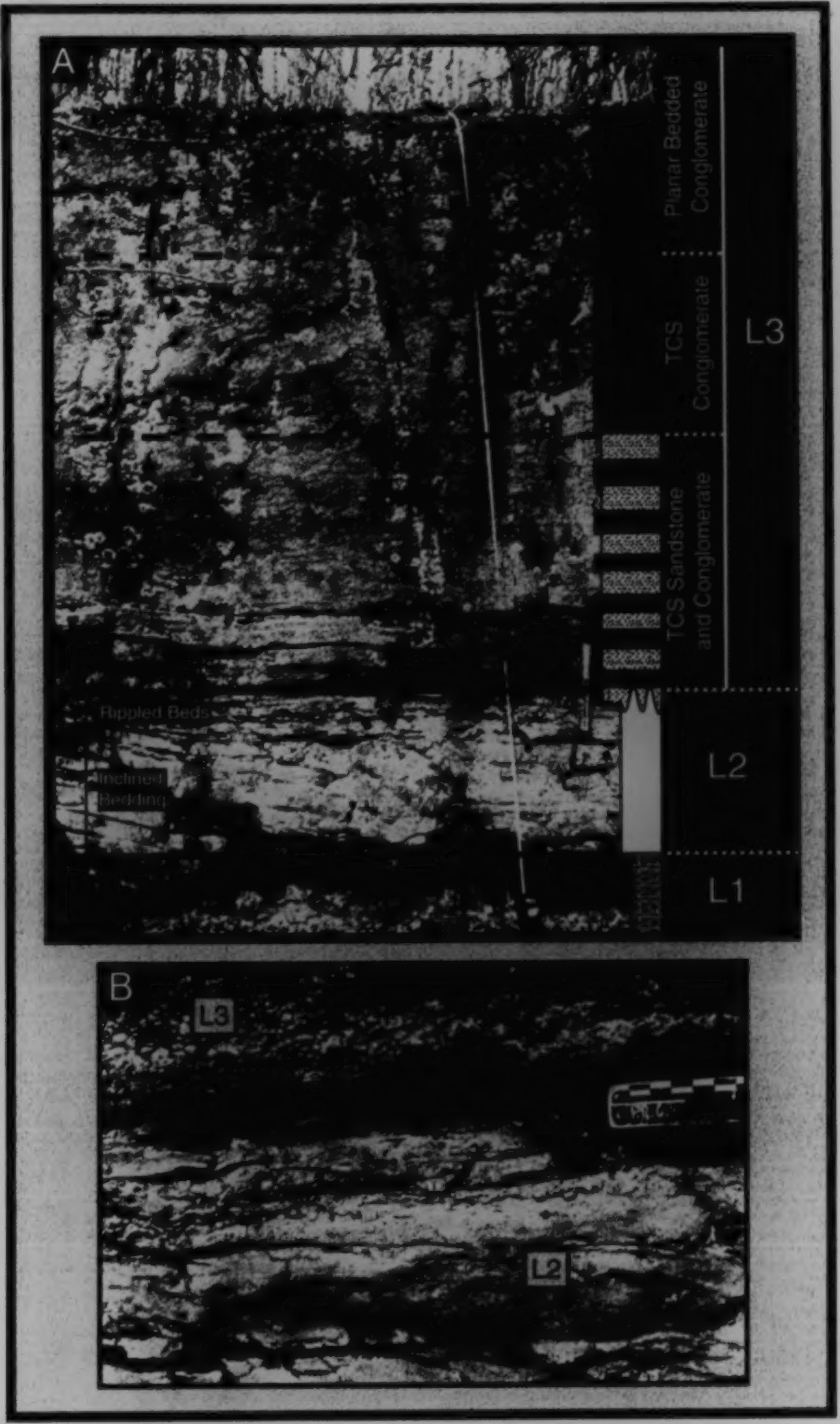
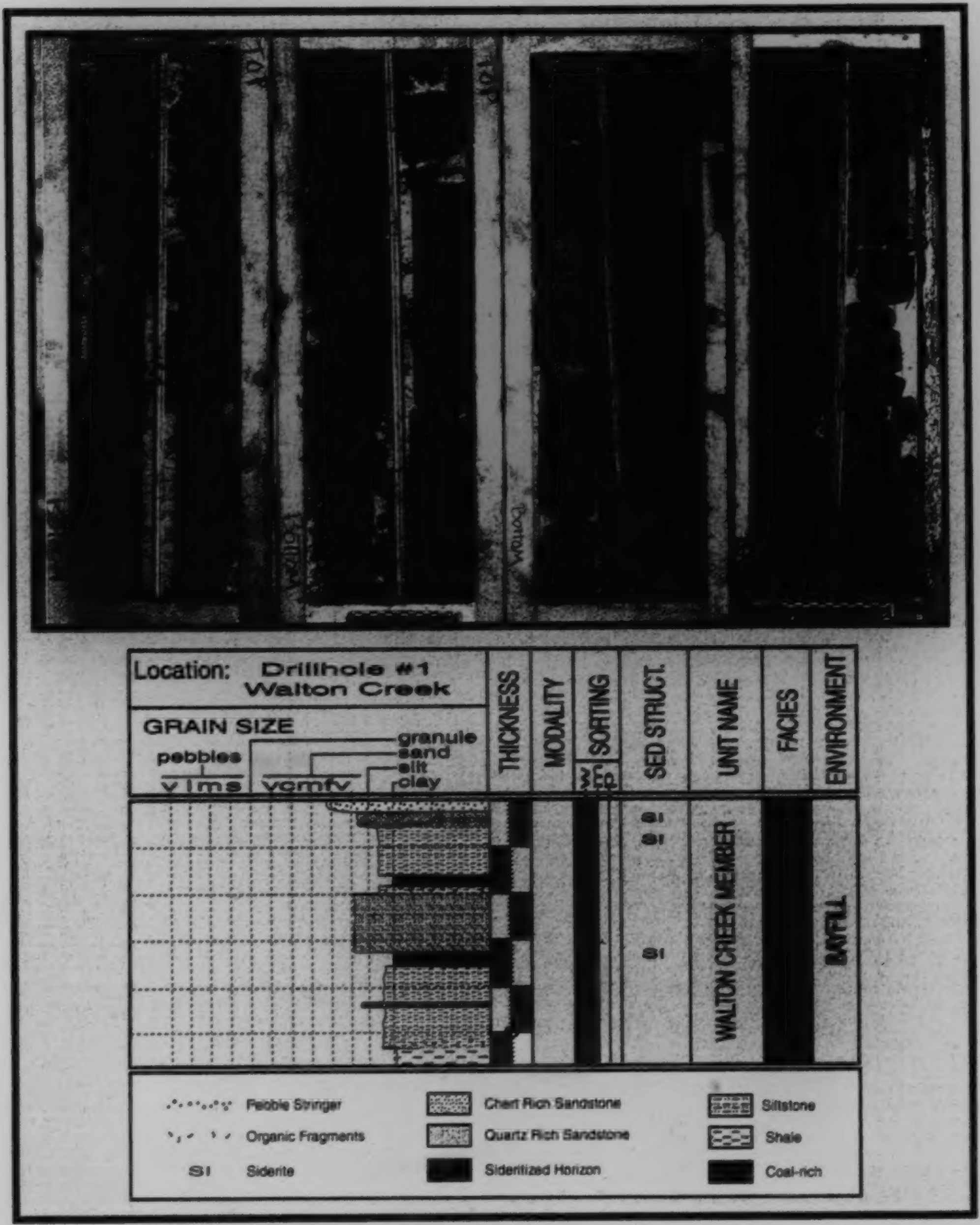

A
Planar Bedded Conglomerate
TCS Conglomerate
TCS Sandstone and Conglomerate
L3
L2
L1
Rippled Beds
Inclined Bedding
B
L3
L2

Figure 2.32 - Core photo-mosaic and strip log description of Walton Creek L4 interval in Drillhole #1 core. Scale in A is in centimeters.


Top
Bottom
Location: Drillhole #1
Walton Creek
GRAIN SIZE
pebbles
v l m s
v c m f v
granule
sand
silt
clay
THICKNESS
MODALITY
SORTING
w m p
SED STRUCT.
UNIT NAME
FACIES
ENVIRONMENT
Si
Si
Si
WALTON CREEK MEMBER
BAYFILL
Pebble Stringer
Organic Fragments
Si Siderite
Chert Rich Sandstone
Quartz Rich Sandstone
Sideritized Horizon
Siltstone
Shale
Coal-rich

CHAPTER 3 – SHOREFACE DISCUSSION

The primary focus of chapter 3 is the interaction of the facies descriptions (outlined in chapter 2) as they are integrated within the framework of a depositional model. The controlling sedimentary processes described in the individual facies interpretations (presented in the previous chapter) will be elaborated on as their interaction, and larger scale controls, are outlined and discussed.

Measured shoreline orientations and local distributions will shed light on the progradational style and direction of the Commotion Creek Cadotte coastal system. Comments will then be made regarding the supply of coarse-grained material to this coastline.

Attempts to place the Commotion Creek study area in a larger, Cadotte basin scale setting, will be made through comparison of regional thickness variations and distinct interval characteristics. This discussion will also outline any potential sequence stratigraphic interpretations applicable to the Commotion Creek Cadotte, by presenting both their strengths and weaknesses.

The chapter will conclude with brief comments regarding the influence of depositional processes on the development, and preservation of reservoir quality sediment accumulations, and their relation to the evolution of a Deep Basin type, conglomeratic, gas reservoir.

3.1 The High-Energy Shoreface and the Storm Dominated Model

The facies assemblage outlined in the previous chapter was interpreted within the context of a storm dominated, coarse grained, high-energy shoreface (and associated ramp and offshore transition)(Figure 3.1). This type of setting has been described by numerous authors for both modern and ancient sand rich systems, however conglomeratic analogues are harder to come by (Hunter et al., 1979; Massari and Parea, 1988; Walker and Plint, 1992; Saunders et al., 1994; Pemberton, 2001). Developing a depositional model for the Commotion Creek Cadotte outcrop section required the incorporation of depositional processes from both modern and ancient, sand dominated, and conglomeratic, coastal settings.

Distal ramp and offshore transition deposits, and their associated processes, will only be briefly discussed. The absence of sand in the distal ramp deposits of Facies A indicates deposition from suspension, below storm wave base. Shoreward of Facies A lay a mixed mud, silt and sand outer offshore transition. This setting is defined by the presence of both suspension, and traction, transported sediments. The storm-wave interpreted bedding style of the fine-grained sandstones supports a locus of deposition above storm wave base. However the presence of low energy, suspension muds and silts suggests prolonged periods of quiescence, and therefore, deposition below fairweather wave base (Table 3.1 and Figure 3.1). As the modal percentage of mud and silt in the sediment decreases, Facies B gives way to Facies C. The absence of low energy suspension deposits in the Facies C exposures signifies either the absence of quiescent conditions, or stronger erosive capability, and frequency, of storms and associated deposits. The transition in bedding style from HCS to SCS within the upper two meters of the facies interval, coupled with the appearance of coarse-grained chert sands and pebbles (as stringers and gutter casts), signifies the approach of shallower water, as well as interaction with nearshore storm processes.

The presence of the abundant hummocky cross-stratified fine sandstones in the outer and inner offshore transition (Facies B and C) provides the primary evidence of intense storm activity acting on this coastal system. These HCS beds also represent one primary variation between the Commotion Creek shoreface model and published high-energy, storm dominated ancient analogues. In most published data, the presence of trough cross stratification is restricted to the upper shoreface, while the lower shoreface is dominated by hummocky to swaley cross stratification (Walker and Plint, 1992; Pemberton, 2001). However in the Commotion Creek model, hummocky cross stratification is restricted to the offshore transition, while both the upper and lower shoreface are dominated by trough cross stratification (Table 3.1). It is concluded from the variations present in the Commotion Creek outcrop exposure, that as the abundance of coarse material in the nearshore is increased, the associated sub-enviroments will concurrently become increasingly dominated by coarser material. Once present in the lower shoreface, the coarse nature of the sediment prohibits the development of hummocky cross stratification, and thus, when the coarse sediment is mobilized, trough cross bedding, by default, becomes the dominant style of bedding. The abundance, and segregation, of finer sand in the offshore transition and coarser chert in the nearshore, may also suggest an abundant, local source for coarse material (possible deltaic influence).

The two variations of the Facies C-D transition, indicate variability in controlling depositional processes. These variations represent 2 distinctly different shoreface states. The Type 1 transitions are interpreted as gradational in nature and would therefore signify normal shoreface progradation, or a shoreline in an unbarred, equilibrium wave state. The abrupt, and more erosional, Type 2 transition has been interpreted as representing the distal, terminal mouths of rip channels. The presence of pebble filled gutter casts and large shallow scours are provided as evidence of the large, along to offshore-dominated, unidirectional currents. The laterally discontinuous nature of both facies transition styles indicates that the controlling process of both transitions is episodic, or at the very least, temporally inconsistent.

Similar variability has been described from the Oregon coast of the United States, in which the modern coarse grained shoreline progrades as an amalgamation of two distinct shoreface morphodynamic states (barred and unbarred). Hunter et al. (1979) concluded that the transitions in shoreline state were controlled by the presence (barred state) and absence (unbarred state) of storm activity. They also described the seasonal control on storm activity, where winter is characteristically stormy, while summer is relatively storm free. In this seasonal model, storm activity would decrease the depositional shoreline dip by eroding proximal nearshore sediments. This sediment is then carried, via transient rip currents, somewhat parallel to shore in the proximal nearshore and then in a more basinward direction further down dip, until the competency of the rip current finally drops, and it becomes depositional.

During fairweather dominated summer months the storm bar material is remobilized as it is transported back up the shoreface by asymmetrical wave fronts until it is eventually welded back onto the upper nearshore. The basic premise of the Hunter et al. (1979) model is that the Oregon coast experiences its most intense erosion during the winter, while summer months support more constructive behavior, and that associated with this seasonality is a change in dominant shoreline state. The balance between the frequency of storm activity during both winter and summer, and both the rate of fairweather reconstruction, as well as sediment supply to the coastline, is extremely important, as it will determine nearshore shoreline behavior. This behavior includes factors such as whether the coastline will prograde, retreat or remain stationary, the rate at which it will do so, and its morphodynamic state.

Rahmani and Smith (1988), Saunders et al. (1994) and MacEachern (1994) have all applied a similar barred shoreface model to the Cadotte Member in other locations throughout the Western Canadian Sedimentary Basin. In all instances the storm generated barred state is characterized by the presence of a sharp transition between hummocky cross stratified, quartz-dominated, fine-grained sandstones and coarse-grained chert-dominated conglomerates to coarse sandstones.

The storm dominated, high-energy shoreface model is supported in the Commotion Creek Outcrop (Figure 3.2). In both the Commotion Creek North and Commotion Creek South locations an obvious progradation is evident. Facies divisions are commonly evident as changes in the slope of the shoreline profile. In Commotion Creek North, a series of interpreted rip channel scours mark a storm erosional profile, however, a definitive storm profile slope could not be determined due to the complexity associated with the different dip directions associated with the orientations of; 1) the wave controlled shoreline orientation, 2) the rip channel state and 3) the periodic, and dominantly two dimensional, preservation of the channels themselves.

Due to the high quality of the exposed fairweather profile, attempts have been made to determine a set of numerical, quantitative, dip oriented dimensions for the various Cadotte sub-environments. Using the average master bedding plane dip values (dip of the topset, clinoform, toeset etc.), facies thicknesses, and assuming a simple right triangle, trigonometry was used in an attempt to derive the landward/basinward widths of the individual facies belts. These facies dimensions are summarized in Figure 3.3. The dip data for Facies A, B and C is somewhat more speculative than that of Facies D, E and F, but is still useful. The dimensional analysis shows that the highest energy, and most coarse-grained chert rich sediment zones of the Cadotte succession are confined to a basinward distance of approximately 200 meters. This 200 m value also approximates the dip-oriented, basinward distance from the top of the beach to where fairweather wave fronts first begin to agitate nearshore sediments (discussed further below). By the same logic, storm enhanced wave fronts begin agitating sediments approximately 1.5-1.6 km offshore.

By integrating facies observations with the interpreted depositional processes it is determined that paleo-wave base for the Cadotte succession was at a water depth of approximately 10 meters. This value is determined using the average thickness of the fairweather shoreface, bounded by the FS/USF (Facies F/E) contact above, and the LSF/OST (Facies C/D) contact below, and agrees well with values ranging between 5-15 m reported by Walker and Plint (1992) for modern environments. Since incoming waves act upon the sediment/water interface at a maximum depth roughly equal to one-half their wavelength, it is presumed that the waves arriving into the Commotion Creek Cadotte nearshore had initial wavelengths of approximately 20 m (Komar, 1976; Walker and Plint, 1992).

Adding the thickness of Facies C and B to the depth of fairweather wave base, it is determined that the incremental wave impact depth attributed to storm wave enhancement lies at a maximum paleo-ocean depth of 50-60 m. This value is reported as a maximum value because due to the poor exposure of Facies B, it could not be confidently determined at what vertical location within the facies, oscillatory/combined flow storm deposits disappeared (storm wave generated deposits) and were replaced by solely unidirectional planar storm beds (interpreted to form below the maximum wave depth of each individual storm). Bourgeois (1980) determined a paleo-storm impact depth of approximately 50 m for deposits of the Upper Cretaceous Cape Sebastian Sandstone of S.W. Oregon. She suggests that shelf storm waves impacting the sea floor at such a depth would have heights of approximately 1.5 m and near-bottom velocities of 12.7 cm/sec. It should be noted that the Cape Sebation Sandstone was deposited in a region characterized by high sedimentation rates and active tectonism (similar to the Cadotte Member paleo-evnvironment).

Although neither of these wave depth values account for post depositional compaction associated with burial, and subsequent diagenesis, the small percentage of each individual sediment grain has actually been dissolved indicates that not much of the original depositional thickness has been destroyed. This raises the level of confidence associated with paleo-water depths and therefore the allocation of fairweather, and storm, wave base.

At the individual clinoform scale of observation, grain size, and subsequently, degree of modality and sorting, variations appear to be somewhat consistent. In all instances, as an individual clinoform was followed down its depositional profile, grain size and degree of modality appeared to decrease, while sorting appeared to increase. This is not to say that all clinoforms are poorly sorted and coarse grained in the upper portions of the shoreface profile and well-sorted fine-grained sediment in their lower reaches. It simply means that if the shoreface is dominated by poorly sorted, highly polymodal, medium to large pebble conglomerate in the upper shoreface (as it is in portions of Commotion Creek North), by the lower shoreface it may be a moderate to poorly sorted, bi to polymodal, granule to small pebble conglomerate. The alternative scenario, prevalent at Commotion West, would have well-sorted, upper very-coarse grained sandstones grading down profile into well sorted, medium to coarse grained sandstones.

The principle complexity in understanding Cadotte sediment grain size variation arises from individual clinoform distribution throughout the study area (strandplain – discussed below). In panel 2 of Figure 3.2, it can be seen that the vertical strip log of CC-5 shows a coarse, polymodal conglomerate unit in orange, underlying a finer grained, more well sorted unit in red. This juxtaposition of grain sizes is due to the presence of a finer grained clinoform building in front of a more coarse grained one. The mid-clinoform of the coarse shingle is overlain by the fine upper-clinoform of the subsequent shingle.

The distribution of clinoforms with similar grain size profiles, although apparently somewhat chaotic, is not entirely random. A few generalized observations were made. First, the bulk of the Commotion West and Commotion East outcrops were dominated by upper very coarse sand. Second, much of Commotion South and the southern portion of Commotion North are characterized by more pebbly conglomerates. Finally, from the northern end of Commotion North to the waterfall, the dominant sediment fines again, as it becomes more granular in nature.

3.2 Shoreline Orientations

The exceptional exposure of the large USF (Facies E) clinoforms allows for the generation of a sparsely populated shoreline orientation map (Figure 3.4). This map was generated by plotting the dip directions of measurements made on the USF clinoforms (and more rarely foreshore swash bed strike) throughout the Commotion Creek study area. To this point in the study the bulk of the shoreface modeling has been focused at the scale of individual clinoforms and the stacking of sedimentary facies. As is apparent from plotted shoreline orientations, the Commotion Creek shoreface appears to prograde as part of a larger amalgamation of numerous shoreface clinoforms, therefore indicating the presence of a larger scale strandplain system. The Commotion Creek strandplain is characterized by coastline orientations that regularly change, however these shoreline variations still remain within the range of established shoreline strike (Figure 3.5). As is evident in the pseudo-strike parallel Commotion West panoramic (Figure 3.5), east-west oriented clinoforms can shift to a northwest-southeast orientation within an apparent pseudo-alongshore distance of approximately 250 m. However due to the lack of a continuous strike exposure of a single clinoform, it cannot be determined whether there is a concurrent grain size variation associated with this coastal reorientation.

Dip-oriented exposures occasionally show a similar change in clinoform orientation. However in some of the dip sections this coastal orientation transition can take place with a basinward distance of 20-25 meters. Figure 3.6 provides an example of how rapidly the coastline can change.

The Nayrait Coast of Mexico provides a possible (albeit not entirely representative) example of how a modern, sand dominated strandplain would behave (Curray and Moore, 1964). Figure 3.7 attempts to place the Commotion Creek study area within the published shoreline orientation map of Curray (1967). This overlay suggests that the Commotion Creek area may represent only a small portion of what could be a much larger coastal strandplain, and that numerous small scale coastal reorientations (exposed within the outcrop) are to be expected if it is, in fact, part of the aforementioned larger system.

3.3 Sediment Source

Sources of sediment in modern coastal settings are commonly attributed to one of three different regions; reworking of shelf/ramp sediments (line source), erosion of coastal headlands and coast lines (line source), and river systems (point source)(Roep, 1984; Roy et al., 1994). The lack of abundant chert-rich sediments in the offshore transition to ramp deposits of the Cadotte member eliminates reworked offshore transition and ramp material as the dominant sediment source. The absence of a stratigraphically underlying hardground suggests a lack of eroded sea cliffs (eliminating coastal headland erosion as a viable option).

This leaves two possible sources for Cadotte coastal sedimentation. The first possibility is the reworking of previous shorelines during coastal transgression. In essence, it represents shoreline erosion coupled with intense sediment winnowing. This type of source would be controlled by wave energy along a laterally continuous coastline, in other words a line process attacking a line sediment source. The resultant associated deposit would include all the coarse grained material from shorelines that were previously eroded, and originally more basinward located, that have been bulldozed into a continuous coastline. It is the author's opinion that these bulldozed and winnowed shorelines should be characterized by more laterally extensive accumulations of somewhat similar sediment.

The second possible source is the reworking of coarse-grained deltaic material (Arnott, 1993). This scenario represents a line process (wave energy) acting on a point sediment source. The resultant deposit should manifest itself as a localized, laterally discontinuous accumulation of coarse-grained material (relative to the dominant shoreline sediment) in regions proximal to the original point source. Subsurface mapping of conglomerates of the Cadotte Member in the Noel, Moose, Sundown and Jackpine areas of Northeast British Columbia support this shoreline source interpretation. Conglomeratic accumulations within these fields map as laterally discontinuous, east-west oriented lenses of coarse-grained shoreline sediment, contained within an overall sandy system (Figure 3.8).

As the Commotion Creek area is approximately 100 km northwest of these producing fields, it cannot be stated with 100% degree of confidence that sediment in the Commotion Creek study area was derived from the same types of sources, in the same ways as Cadotte shoreline sediment in established gas fields. The relatively large abundance of coarse grained material present in both the upper and lower shoreface of the Commotion Creek shoreline (relative to the more mixed conglomeratic to coarse sandy systems in the subsurface), does suggest a higher local abundance of coarse sediment, and for this reason the reworked point source model is favored.

Both the reworked coastline, and reworked point source scenarios are viable options for a Cadotte locus of sediment, and given the relatively small geographic scale of the study, it cannot be conclusively determined which model is fully correct. However, due to regional scoping, and an apparent localized abundance of sediment (manifested as thick facies of coarse sediment), a "proximal to a point source" or reworked deltaic setting, is favored.

3.4 Regional Integration

Its difficult to constrain the Commotion Creek shoreface-strandplain system sequence stratigraphically, is difficult. The scale of the study is at more the parasequence level and the availability of detailed internal biostratigraphic information is extremely limited, to virtually absent. These challenges do not mean that comments cannot be made regarding the regional behavior of the Cadotte, just that much of this discussion will be more speculation than thoroughly supported, and presented, detailed geologic analysis (however much of it is influenced by the authors regional subsurface experience with the unit).

3.4.1 Regional Thickness Variations

One obvious and measurable difference between the Commotion Creek Cadotte section and subsurface equivalents located within the more south, and east, producing gas fields, is thickness. As can be seen in Figure 3.9, the Cadotte thins in a southern, and eastern, direction. This regional thickness variation was probably influenced by multiple factors, of which a few are discussed in more detail below.

The first major influence on interval thickness is regional variations in coastal accommodation. Large values of Cadotte (and Hulcross) thickness, relative to the Wapiti and Elmworth gas fields, suggest that deposition in the vicinity of the Commotion Creek study area occurred along steeper dipping portions of the foreland basin's western (easterly to northerly dipping) ramp. As well, as far north as it is, the study area is located in a setting proximal to the Dawson Creek Graben Complex, and consequently, is also subject to its influence. As was discussed in the opening chapter, the Dawson Creek Graben Complex made up an integral part of the subsiding Peace River Embayment.

Being located on a steep dipping ramp margin, in a proximal location to an active graben complex, suggests that the Commotion Creek study area is in a high accommodation setting (compared with areas to the southeast, like Wapiti and

Elmworth), and that the primary control on the generation of accommodation space is tectonic in nature.

Roy et al. (1994) labeled ramp/substrate dip angle as the primary influence on the coastal sediment budget. He concluded from modern studies, that for ramps/substrates dipping over 1 degree, sand will have a tendency to move into the offshore, while for regions dipping less than 1 degree it will preferentially move onshore. This relationship may be present on a regional scale within the Cadotte. Areas in the southeast with a more mixed sand, silt and mud inner O.S.T. (Table 3.1) could be associated with shallower ramp dip angles as paleogeographically they are further away from the deepest portions of the Middle Albian Foreland Basin. The sand rich inner O.S.T. of the Commotion Creek study area, being located in a setting more proximal to both the Foreland Disturbed Belt and the Dawson Creek Graben Complex, represent deposits of a steeper dipping ramp.

The apparently overthickened Cadotte intervals evident on the gamma ray log cross section in Figure 3.9, may also be influenced by this transition from the mixed sand, silt and mud inner offshore transition in areas like Wapiti and southern Noel, to an increasingly sand dominated one, at Sundown, East Pine and Commotion Creek. Since the gamma ray log is simply measuring inherent radioactivity in the sediment (of which chert and quartz have little), its apparent overthickening does not necessarily fully represent a significant increase in shoreface sub-environment thickness, and in fact, may be somewhat misleading due to a basin scale lateral increase in Facies D sand content.

Finally, the increase in O.S.T. quartz sand may also suggest that concurrent with a north and westward increase in accommodation and ramp dip angle, is an increase in the supply of sediment to the coastline, and therefore by inference, a more source proximal setting. This scenario seems likely, as both the Commotion Creek and Dokie Ridge study areas are located in regions that are proximal to the paleo-deformation front (Figure 1.15). If the point source model for Cadotte shoreline sediment (discussed in 3.3) is believed, then areas around Commotion Creek would be characterized by a higher concentration of point sources that have traversed shorter distances carrying less mature sediment (they may also be somewhat laterally amalgamated creating the appearance of having been derived from a line source).

3.4.2 Systems Tracts

Attempting to label Cadotte deposition in the Commotion Creek area as occurring during a highstand, lowstand, falling stage or transgressive systems tract is tenuous, as there is supporting evidence, and lack of evidence, for almost all the possibilities. The most important stratigraphic surfaces used to constrain any Commotion Creek Cadotte systems tract allocation are the interval's upper contact (FA 1/FA 2 contact) and its internal Facies C/D transition. In the absence of supporting biostratigraphic evidence, characteristics such as sediment grain size and sorting, as well as, facies thickness and stacking, play increasingly key roles in potential systems tract assignment. This discussion will focus on transgressive (TST), falling stage (FSST) and highstand (HST) sedimentation.

Coastal deposition during a trangression is characterized by high accommodation (due to continually rising relative sea level). However coincident with this high accommodation is decreased ramp gradients (as the shorelines are prograding over previous coastal plains) and an overall retrogradational behavior. Shorelines commonly manifest themselves as barrier islands (with associated well-developed lagoons), and will receive the bulk of their sediment load by reworking material from transgressed regions of the shelf or ramp (Reinsen, 1992). In wave-dominated settings, sediment is expected to be well sorted, and show signs of winnowing and lateral consistency (Heron Jr. et al., 1984). This systems tract has been eliminated as a possibility for the succession at Commotion Creek as the Cadotte has been interpreted as being part of a large-scale strandplain system. Thus there is no evidence of back stepping, retrogradational, barrier island-type shoreface behavior, nor evidence of prolific, well developed lagoons, characteristic to TST's (however, this systems tract has applicability to the overlying Walton Creek unit).

An alternate systems tract scenario may be the presence of a pronounced regional Cadotte cyclicity controlled by tectonic events in the adjacent foreland fold and thrust belt. This hypothesis would have a regional, fine to medium grained, quartz sand dominated Cadotte shoreline/strandplain complex that has been subjected to a deepening (possibly associated with tectonically driven thrust sheet loading). Following the flood, areas proximal to the highest rates of erosional unloading experience a rapid, to forced regression of a chert conglomerate dominated, Cadotte shoreline system. This second, potentially sharp based conglomeratic shoreline system, would be emplaced within the falling stage systems tract, as the coastline is being "forced" out into the basin by a tectonically induced fall in relative sea level (Plint, 1988). The preserved section would contain a sequence boundary on its upper contact and a regressive surface of marine erosion between the quartz sandstones and chert conglomerates. The regressive surface of marine erosion should be mappable and regional in extent.

Further, concurrent with the development of a regressive surface of marine erosion may be the incision of large valley systems (when changes in continental and coastal plain gradient exist) (Plint and Nummedal, 2000). Figure 3.9 clearly shows evidence of two possible large-scale channels in the regional Cadotte section. Both of the channels in the cross section are larger than the scale of one well, and can been mapped to define distinct valley networks (Hayes, 1988).

The sharp nature of the Type 2 Facies C/D transition at Commotion Creek could be interpreted as representing a regressive surface of marine erosion (RSME), and therefore indicative of a falling stage systems tract (Posamentier et al., 1992). Support for this interpretation might be drawn from the presence of gutter casts in the upper reaches of Facies C (Plint and Nummendal, 2000). However, the Facies C gutter casts show no signs of having oversteepened walls (which would indicate a semi lithofied substrate), and in fact, can be explained most simply, as representing small unidirection flows scouring into soft, unconsolidated sand. The presence of punctuated transition zones (Type 1 transitions) seems problematic in this model as well, as it is thought that since the regressive surface of marine erosion is a significant unconformity, it should be prevalent over a relatively large distance as a distinct surface, and not show the kind of small-scale variation described from Commotion Creek.

For these reasons, the allocation of the Commotion Creek outcrop to a falling stage systems tract is considered less likely.

Highstand scenarios are characterized by progradation during an overall rise in relative sea level (Posamentier and Allen, 1999). The defining characteristics of this systems tract are sedimentation rates large, and rapid enough to allow the shoreline to prograde into ever increasing water depths. This behavior suggests a large volume of sediment, as well as, a high degree of coastal accommodation. The HST model agrees very well with the observed Cadotte unit present at Commotion Creek with one primary exception. Coincident with the high level of coastal accommodation, is an associated high level of coastal plain accommodation. This situation would encourage the deposition, and preservation, of non-marine sediments, in the continually vertically aggrading coastal plain (Milton and Bertram, 1995). At Commotion Creek, Facies Association 2 is capped, not by a conformable continental assemblage, but rather by a sharp transition to brackish bay mudstones (flooding surface). Further complicating the issue is the fact that the Walton Creek flooding surface appears to show no signs of significant erosional removal of the Cadotte shoreline associated sediments. Absolution of this problem is gained by considering the rate of progradation compared to the slowing rate of relative sea level rise (throughout the life of highstand conditions). Although an aggrading coastal plain sedimentary package is expected immediately overlying backshore deposits of Facies G, Emery and Myers (1996) point out that during late highstand, when the rate of relative sea level rise has slowed, aggradation gives way to regression, and the shoreline begins to prograde more rapidly, marked by the absence of an appreciably thick coastal plain assemblage (as it begins to transition into a period of falling stage).

In order to maintain highstand progradation extremely high rates and volumes of sediment are required. Once that material is brought to the coastline, it is deposited in increasingly deeper water depths on a more steeply dipping ramp/substrate gradient. This type of scenario fits interpretations discussed in previous sections of the thesis and consequently, is assumed to be most likely

Finally, adding further strength to the interpretation of a highstand setting is the presence of the underlying Hulcross. The thick and fine-grained nature of the Hulcross shales and silstones is indicative of deposition during an overall transgression. The presence of regional resistivity wireline log markers, present regionally throughout the Hulcross/Harmon may indicate the presence of at least one (but possibly more) major marine flooding surfaces. These pseudo-condensed sections may represent downlap surfaces, common to the base of a highstand systems tract. As well, and even more basic, according to systems tract models, a coastline simply cannot go from a state of transgression to a state of falling stage without some highstand turn around point (Posamentier and Allen, 1999).

Although deposition during highstand conditions is the most likely interpretation for the Commotion Creek study area, it does not suggest that regionally, the Cadotte is always in a highstand state. The presence of the Noel incised valley as mapped by Hayes (1988), as well as potential falling stage shorelines, often hypothesized yet unpublished, in Wapiti, suggests that punctuated relative sea level falls periodically interrupt Cadotte highstand progradational episodes.

3.5 Comments on Reservoir Development and Distribution

One of the goals of this study was to gain an understanding about, and draw conclusions regarding, reservoir development and preservation. Unfortunately due to the consistent nature of the coarse-grained sediment, ideal dimensions of the reservoir quality conglomerate could not be ascertained (as the extent of conglomerate is larger than the outcrop exposures). However, the dimensional analysis may help shed a little light on the feasibility of Cadotte reservoir exploration strategies and could be used to further model reservoir depletion.

Existing knowledge of conglomeratic, deep basin reservoirs indicates that the principle reservoir quality sediment is located within the foreshore of the prograding coastal assemblage (Moslow, 1998). Beyond this, not much can be said other than the reservoirs, and therefore the interpreted coastlines, usually have an east-west orientation (Figure 3.8). A common joke after a new Cadotte pool has been found is to hold up a ruler and call it a Cadotte exploration tool. The study at Commotion Creek demonstrates that although the primary conglomerate body (the strandplain) may be oriented in a west-east to northwest-southeast orientation, the orientation of individual clinoforms (or shorefaces) may in fact show constant variations. This is important to understand as it will exert a strong influence on reservoir volume and drainage.

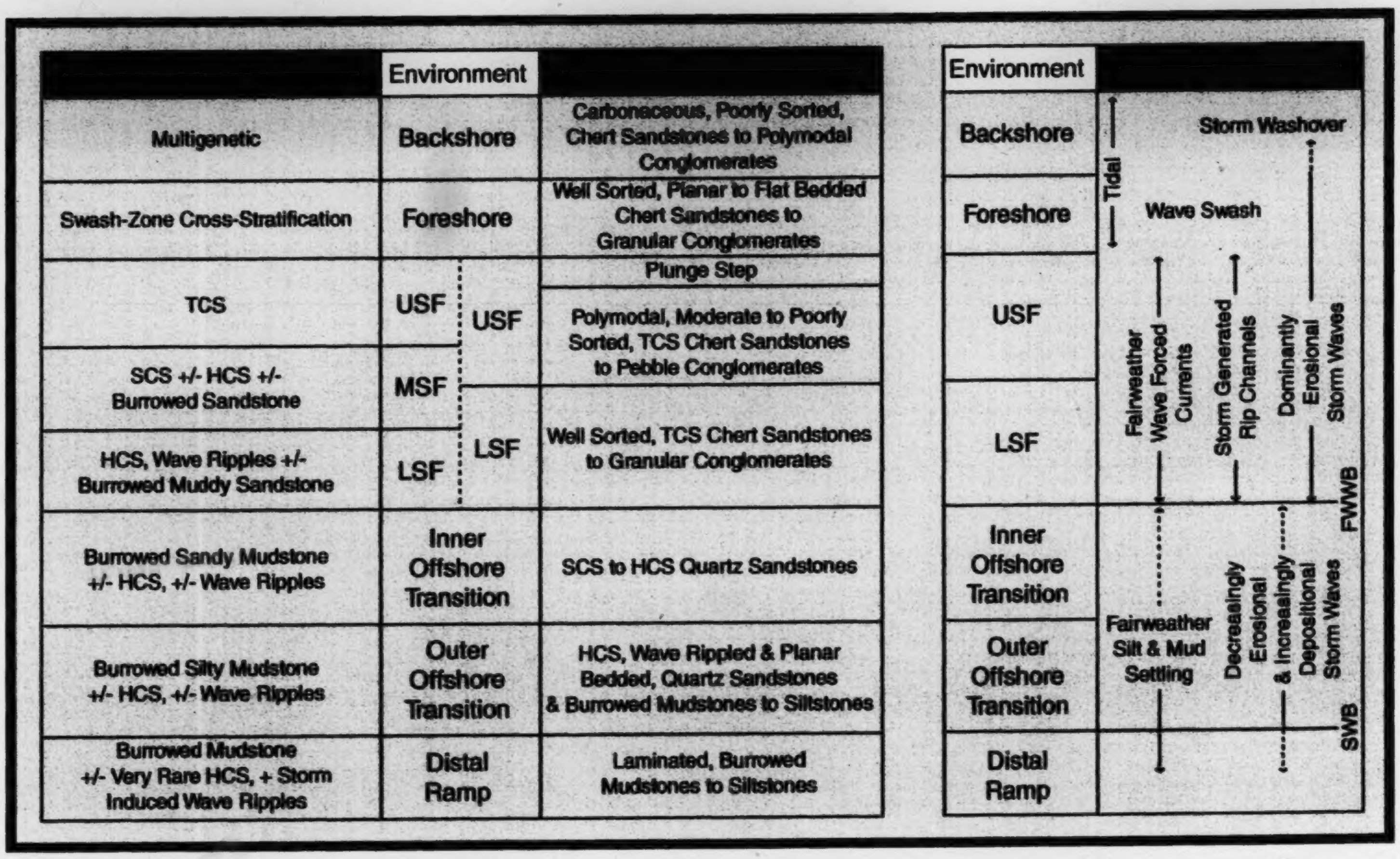
The unpredictable nature of grain size distributions throughout the Commotion Creek area prohibits much in the way of exploration-beneficial understanding, however a few comments can be made from the dimensional analysis.

A facies belt width, at the scale of an individual clinoform, for the principle reservoir unit (foreshore) is approximately 50 meters. This suggests that correlations of like facies from one wellbore to another will cross a large number of individual clinoforms. For illustration purposes assume a well spacing of one kilometer, even though tens of kilometers may in fact be more the norm, at that scale one correlation may in fact cross up to 20 complete, and individual clinoforms (and that is only if they are correlated in a perfect dip oriented line). Each of these clinoforms may have unique grain sizes, modality and sorting, all impacting the reservoir by constantly changing the nature of the flow unit.

Another final conclusion from the dimensional data impacting hydrocarbon exploration relates to the width of the foreshore and shoreface (including the facies C/D transition zone). This value is on the order of approximately 205 meters. The somewhat small distance indicates that much of the chert-rich, coarse-grained sediment is confined to the foreshore and shoreface zones and does not interfinger over a very large distance with the inner offshore transition. This relationship suggests that any attempts to use pebbles in the proximal offshore transition as "in front" indicators would require moving south a minimum of 156 meters, while coarse grained deposits in an upper shoreface setting may only require moving landward 50 or so meters.

In short, due to the extremely localized nature of this study, conclusions related to increasing drilling success percentages while exploring for conglomeratic Cadotte reservoirs are minimal. However, at the scale of the reservoir, increased understanding of Cadotte progradational style and behavior can be used to better model reservoir drainage and plan development drilling.

Table 3.1 – Table summarizing the Commotion Creek shoreface model and comparing it with an established sand dominated classification (from Pemberton et al, 2002). Note the contrasting depositional sedimentary characteristics of the coarse grained Commotion Creek shoreface. Right hand side of table breaks down depositional processes and highlights the approximate location of fairweather (FWWB) and storm (SWB) wave bases.



	Environment		
Multigenetic	Backshore		Carbonaceous, Poorly Sorted, Chert Sandstones to Polymodal Conglomerates
Swash-Zone Cross-Stratification	Foreshore		Well Sorted, Planar to Flat Bedded Chert Sandstones to Granular Conglomerates
TCS	USF	USF	Plunge Step Polymodal, Moderate to Poorly Sorted, TCS Chert Sandstones to Pebble Conglomerates
SCS +/- HCS +/- Burrowed Sandstone	MSF		
HCS, Wave Ripples +/- Burrowed Muddy Sandstone	LSF	LSF	Well Sorted, TCS Chert Sandstones to Granular Conglomerates
Burrowed Sandy Mudstone +/- HCS, +/- Wave Ripples	Inner Offshore Transition		SCS to HCS Quartz Sandstones
Burrowed Silty Mudstone +/- HCS, +/- Wave Ripples	Outer Offshore Transition		HCS, Wave Rippled & Planar Bedded, Quartz Sandstones & Burrowed Mudstones to Siltstones
Burrowed Mudstone +/- Very Rare HCS, + Storm Induced Wave Ripples	Distal Ramp		Laminated, Burrowed Mudstones to Siltstones

Environment
Backshore
Foreshore
USF
LSF
Inner Offshore Transition
Outer Offshore Transition
Distal Ramp
Tidal
Storm Washover
Wave Swash
Fairweather Wave Forced Currents
Storm Generated Rip Channels
Dominantly Erosional Storm Waves
FWWB
Fairweather Silt & Mud Settling
Decreasingly Erosional & Increasingly Depositional Storm Waves
SWB

Figure 3.1 – Dip oriented cross section of proposed Cadotte Commotion Creek storm dominated, high energy, coarse-grained shoreface. Average facies thicknesses and facies color coding is shown at left of cross section (thicknesses not to scale). Dashed black line represents fairweather (summer) profile while dashed red line outlines storm (barred) profile. Dashed red arrow signifies migration of inner storm generated bar down the shoreface profile to the base of the lower shoreface.

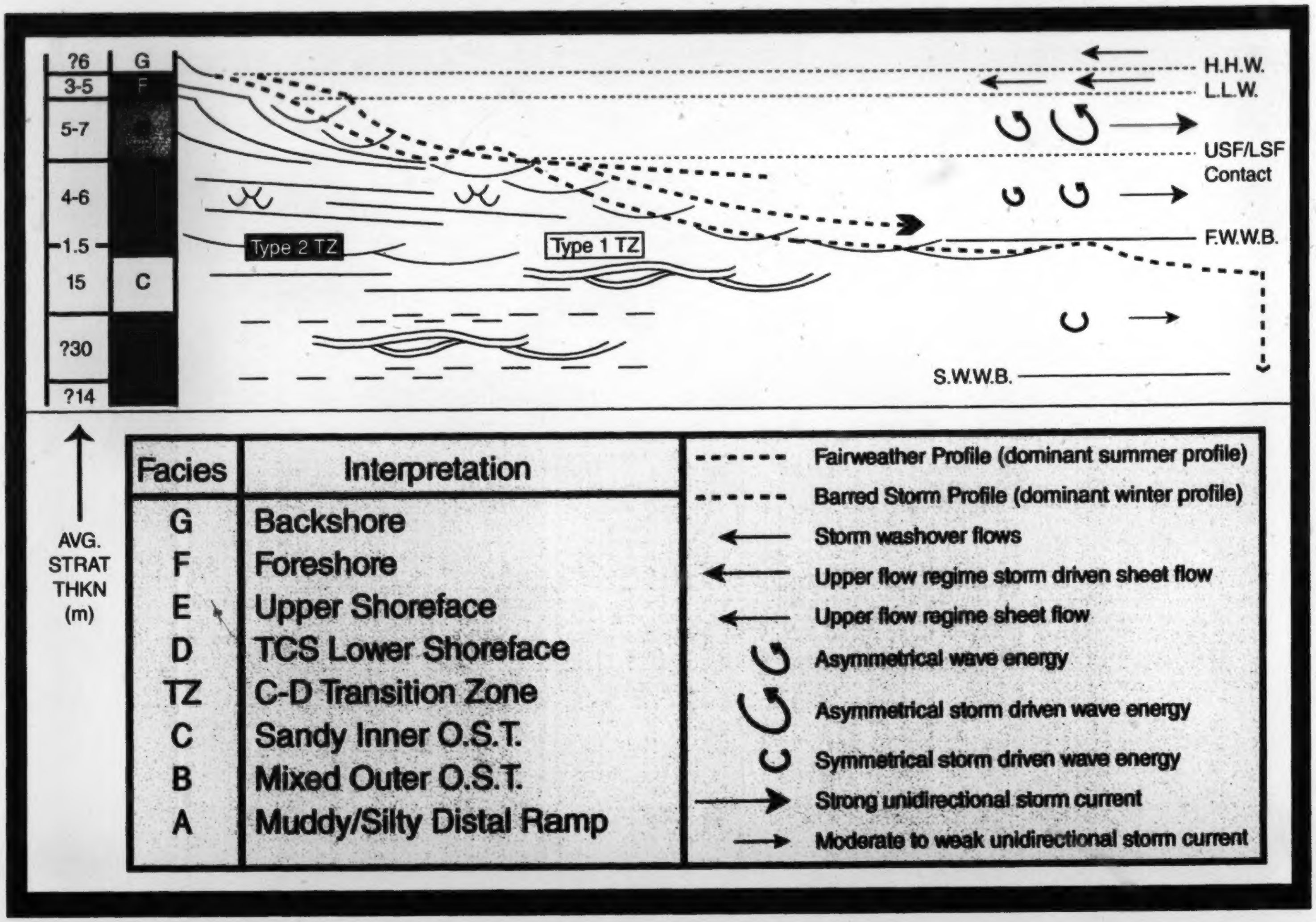

?6
3-5
5-7
4-6
1.5
15
?30
?14
G
F
C
AVG. STRAT THKN (m)
H.H.W.
L.L.W.
USF/LSF Contact
F.W.W.B.
S.W.W.B.
Type 2 TZ
Type 1 TZ
Facies
Interpretation
G Backshore
F Foreshore
E Upper Shoreface
D TCS Lower Shoreface
TZ C-D Transition Zone
C Sandy Inner O.S.T.
B Mixed Outer O.S.T.
A Muddy/Silty Distal Ramp
Fairweather Profile (dominant summer profile)
Barred Storm Profile (dominant winter profile)
Storm washover flows
Upper flow regime storm driven sheet flow
Upper flow regime sheet flow
Asymmetrical wave energy
Asymmetrical storm driven wave energy
Symmetrical storm driven wave energy
Strong unidirectional storm current
Moderate to weak unidirectional storm current

Figure 3.2 – Annotated panoramic of Commotion Creek North (1) and South (2) outcrops with litholog overlay. Yellow lines delineate facies boundaries while the remaining lines represent depositional surfaces color coded by facies (Facies G - green, Facies F – blue, Facies E – orange, Facies D – red). Facies color-coding is also present along the left margin of each figure. Dashed red line in CC-North panoramic denotes approximate trace of storm profile in the upper shoreface while concave up red lines represent the outline of rip channel scours in Facies D. North is to the left in both panoramics (see location photo).

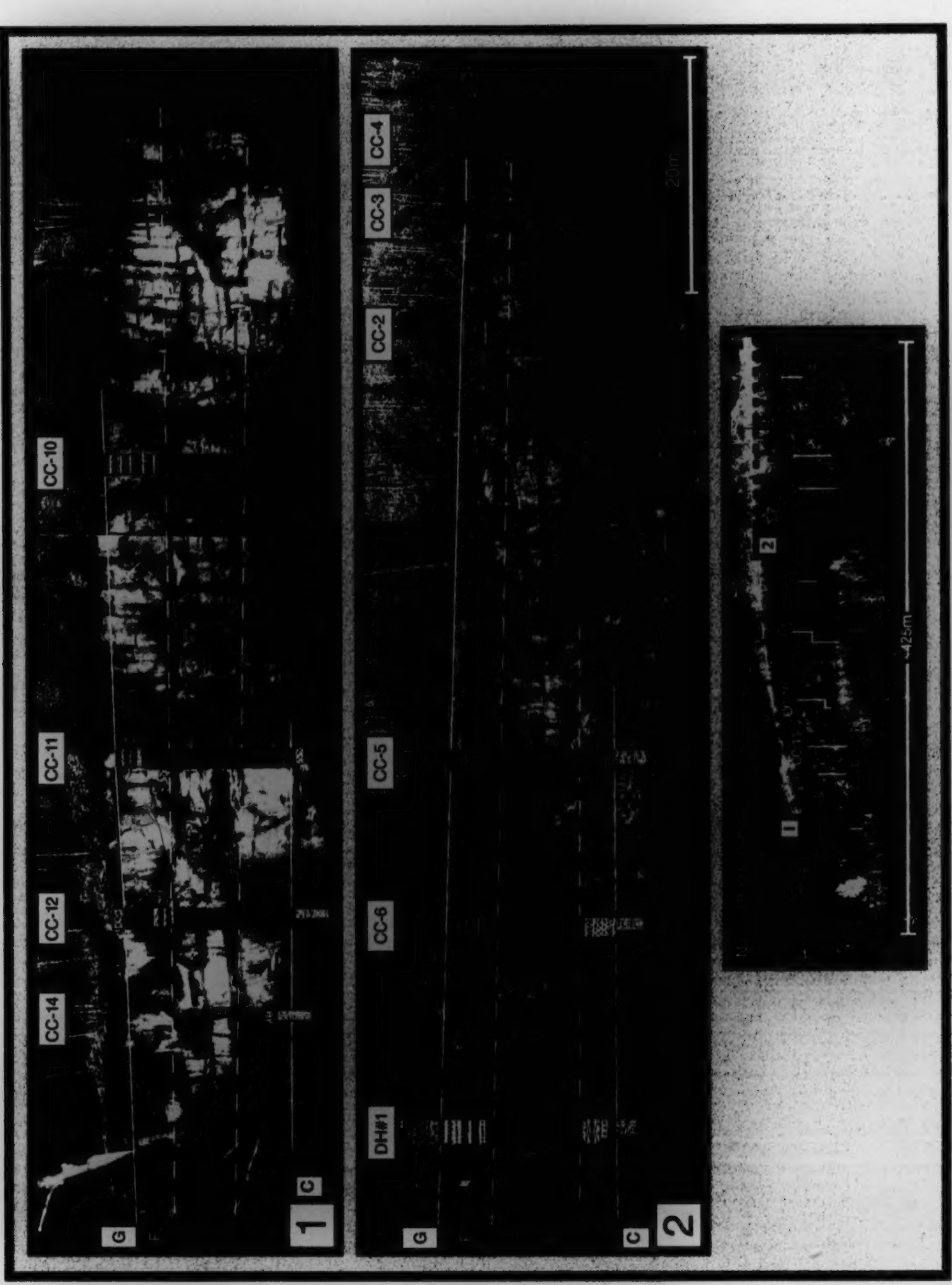
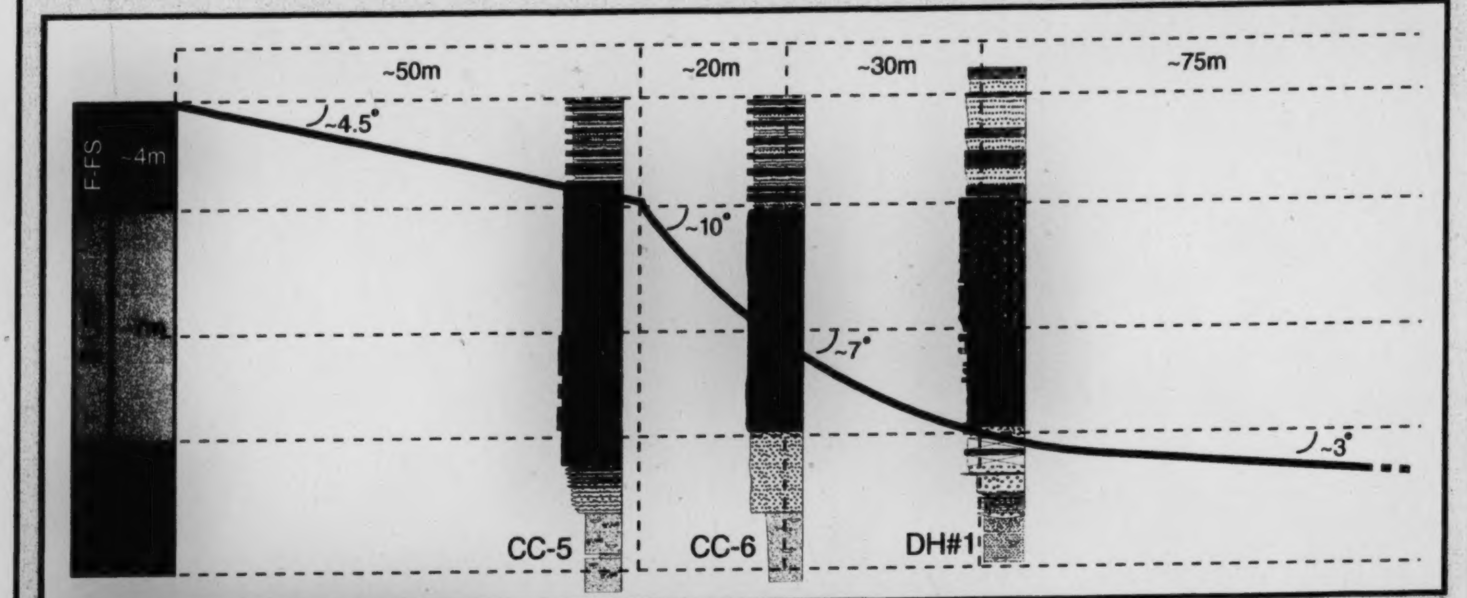
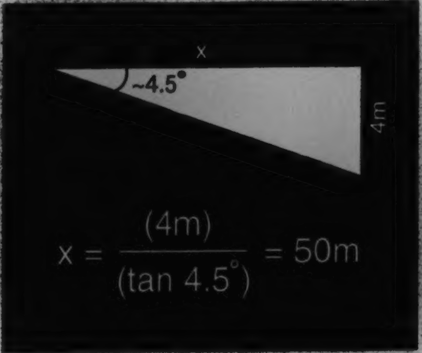

1
G
C
CC-14
CC-12
CC-11
CC-10
2
G
C
DH#1
CC-6
CC-5
CC-2
CC-3
CC-4
20m
1
2
~425m

Figure 3.3 – Geometric breakdown of a single Commotion Creek Cadotte shoreface clinoform. Facies are color coded for ease of comparison with other thesis figures. Two dip angles are reported for Facies E (upper shoreface) as the clinoforms are oblique in nature and therefore dip at shallower angles down the profile. Adding the widths of Facies D, E, and F, as well as, the shoreface/inner offshore transition-transition zone, gives a maximum foreshore and shoreface width of approximately 205 meters. The relatively low value of this measurement suggests that coarse material is trapped in the nearshore while more basinward deposits are finer in nature.


~50m
~20m
~30m
~75m
F-FS
~4m
~4.5°
~10°
~7°
~3°
CC-5
CC-6
DH#1



$$x = \frac{(4m)}{(\tan 4.5^{\circ})} = 50m$$

FACIES	ENVIRONMENT	DIP	HEIGHT	WIDTH
		~3°	~1.5m	~30m
C	INNER O.S.T.	~2-1°	~15m	~500m
B	OUTER O.S.T.	~2-1°	~30m	~850m
		~2-1°	~14m	~400m

Figure 3.4 – Shaded topographic relief map of the Commotion Creek study area with overlay of variations in shoreline strike (black dashed lines). Orientations were obtained from measuring the strike of upper shoreface clinoforms (Facies E) as well as rare values from shallowly dipping swash beds (Facies F). The term swash bed is used to describe the seaward dipping planar beds commonly found in the Cadotte foreshore. All measured orientations fall within a range between 90-270 and 135-315 degrees.

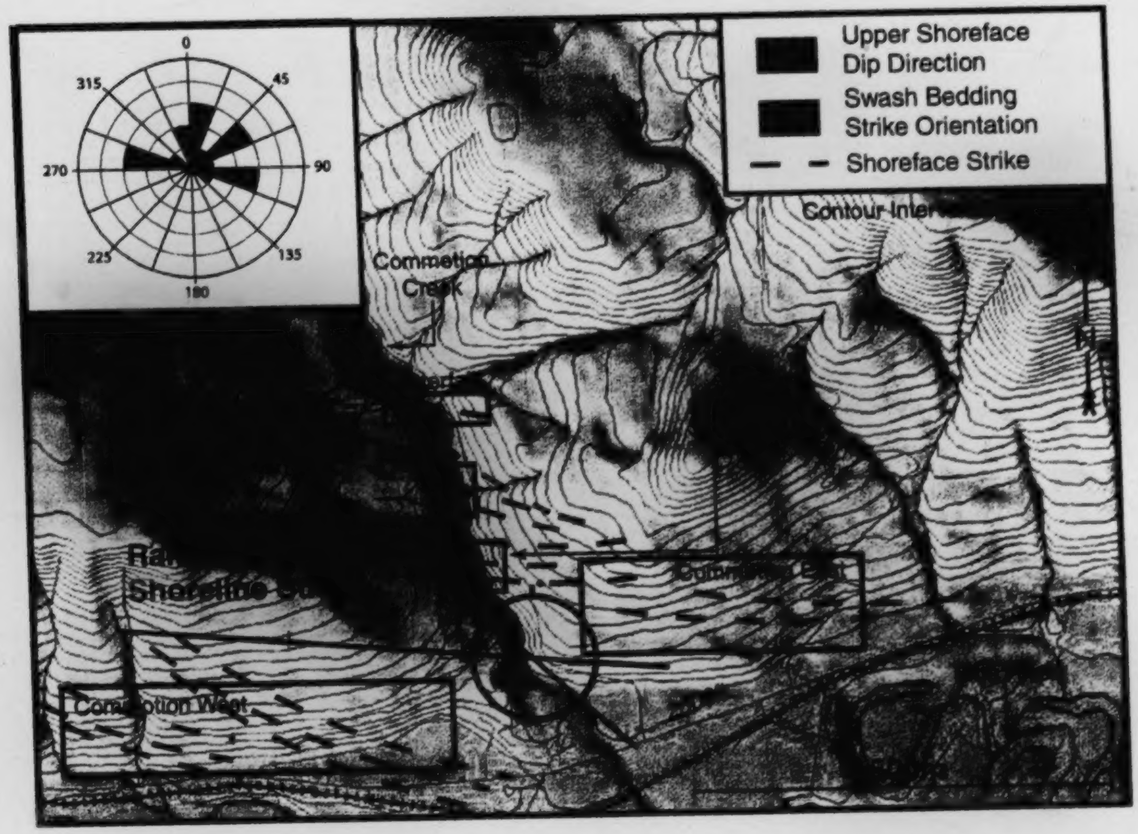

0
45
90
135
180
225
270
315
Upper Shoreface Dip Direction
Swash Bedding Strike Orientation
Shoreface Strike
Contour Inter
Commotion Creek
Commotion West
Shoreline
N

Figure 3.5 – Approximately east-west oriented Commotion West panoramic with litholog overlay. Figure shows eastward steepening of Facies E (USF) clinoforms. This eastward steepening indicates the approach of a more northwest-southeast oriented coastline. Orange squares show approximate shoreline strike at locations of logged sections. Both lithologs show similar lithologies and grain sizes.

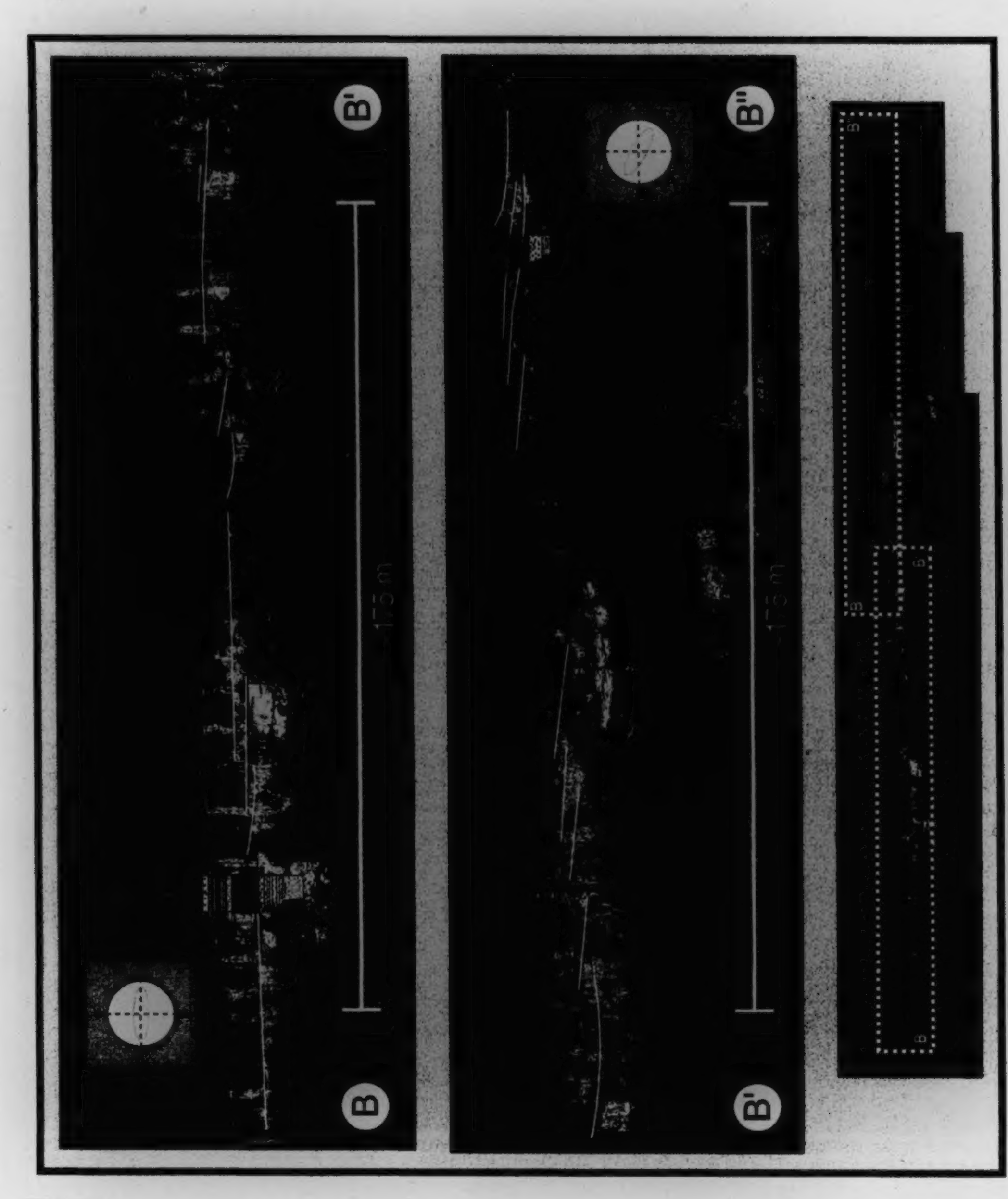

B'
B
~175 m
B''
B'
~175 m
B'
B
B'

Figure 3.6 – The Parker panoramic. A) Detailed panoramic immediately south of the Commotion Creek waterfall at the northern end of the canyon. Panoramic shows the presence of 7 individual shoreface clinoforms characterized by 2 distinct orientations (red and yellow). B) Rose diagram shows orientations of both sets of clinoforms. C) Schematic map/aerial view cartoon, illustrating possible scenario to describe shoreline orientation variation. Rob Parker for scale.

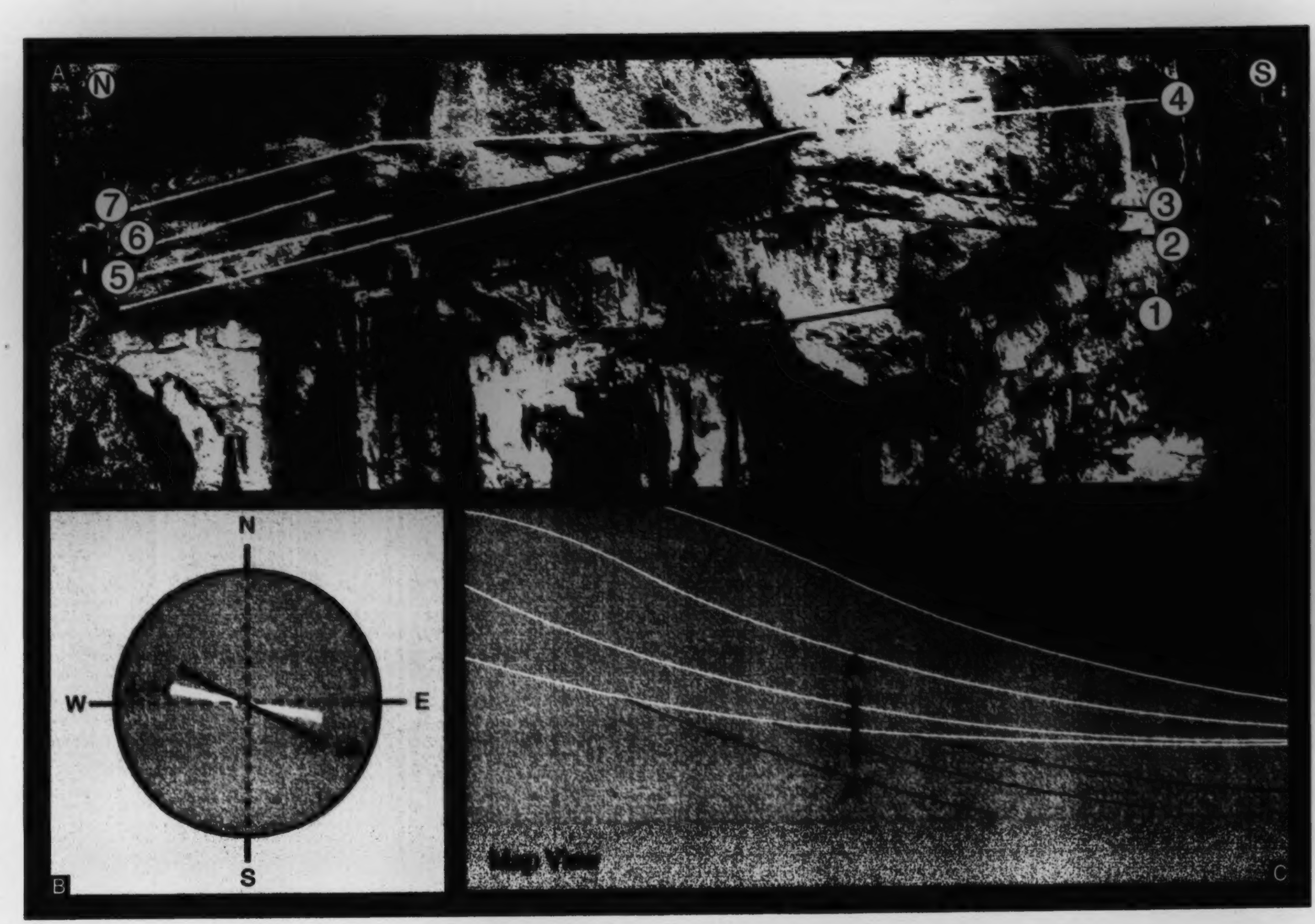

A
N
S
4
7
6
5
3
2
1
B
N
W
E
S
Map View
C

Figure 3.7 – A) Map of the Nayarit coast showing well developed sandy strandplain, highlighted by coastline parallel beach ridges (Curray et al., 1967). Red box represents scaled dimensions of the Commotion Creek study area. B) Commotion Creek study area (creek valley outlined in green) with overlay of shoreline orientations (red lines).

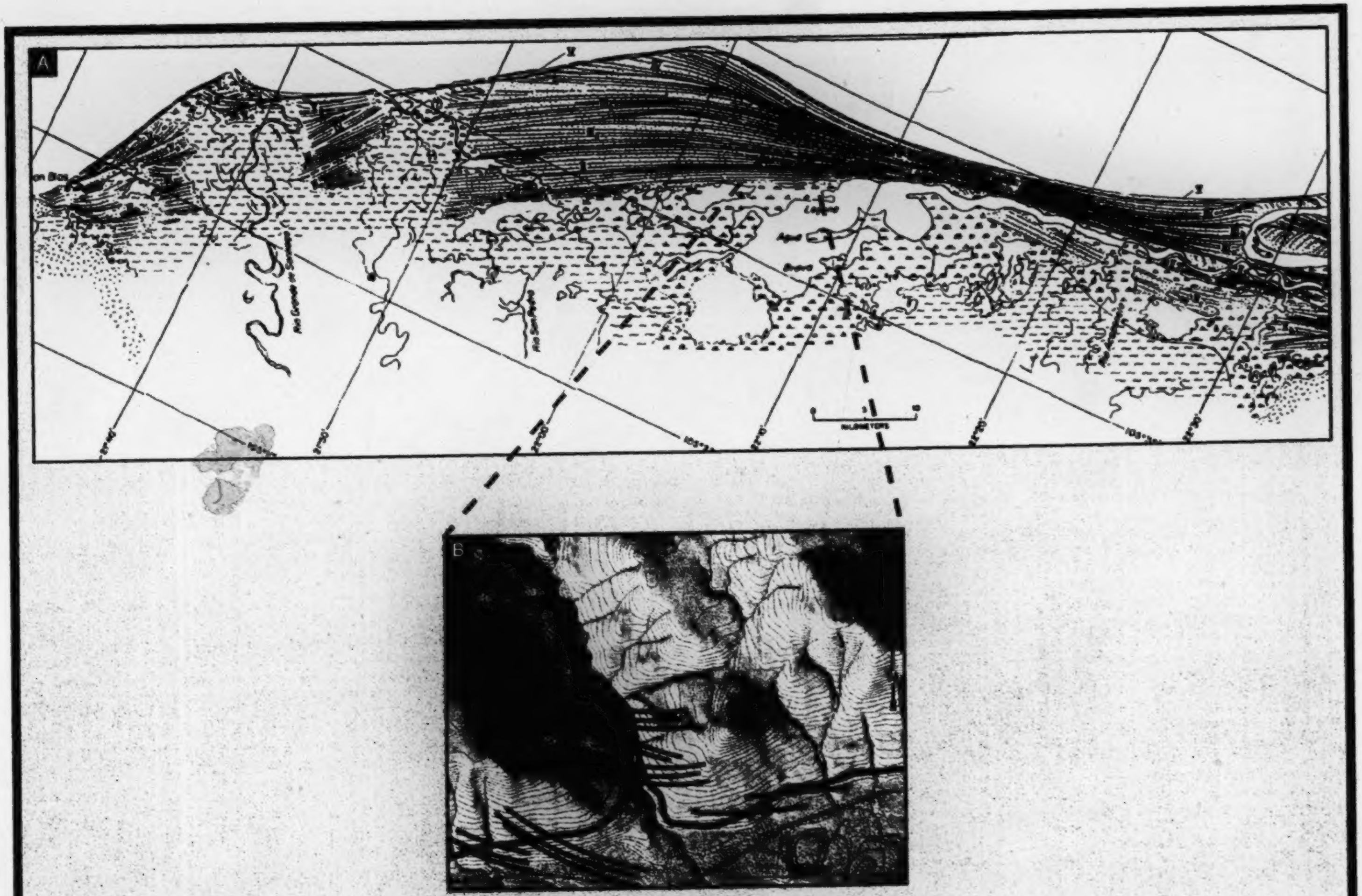

A
an Blas
Rio Grande de Santiago
Rio San Pedro
Laguna
Agua
Brava
0
5
10
KILOMETERS
B

Figure 3.8 – A) Nayarit Coast (from Curray et al., 1967), overlain with scaled outline of Noel map area (B). Commotion Creek study area (C) scaled as an overlay on Noel subsurface shoreline map (map courtesy of BP Canada). Noel map shows common east-west mapping style of subsurface Cadotte shorelines, when in fact, it is likely that although Cadotte strandplains may be oriented east-west, individual shoreface clinoforms (which make up the larger scale strandplain) may show variable values of coastline strike.

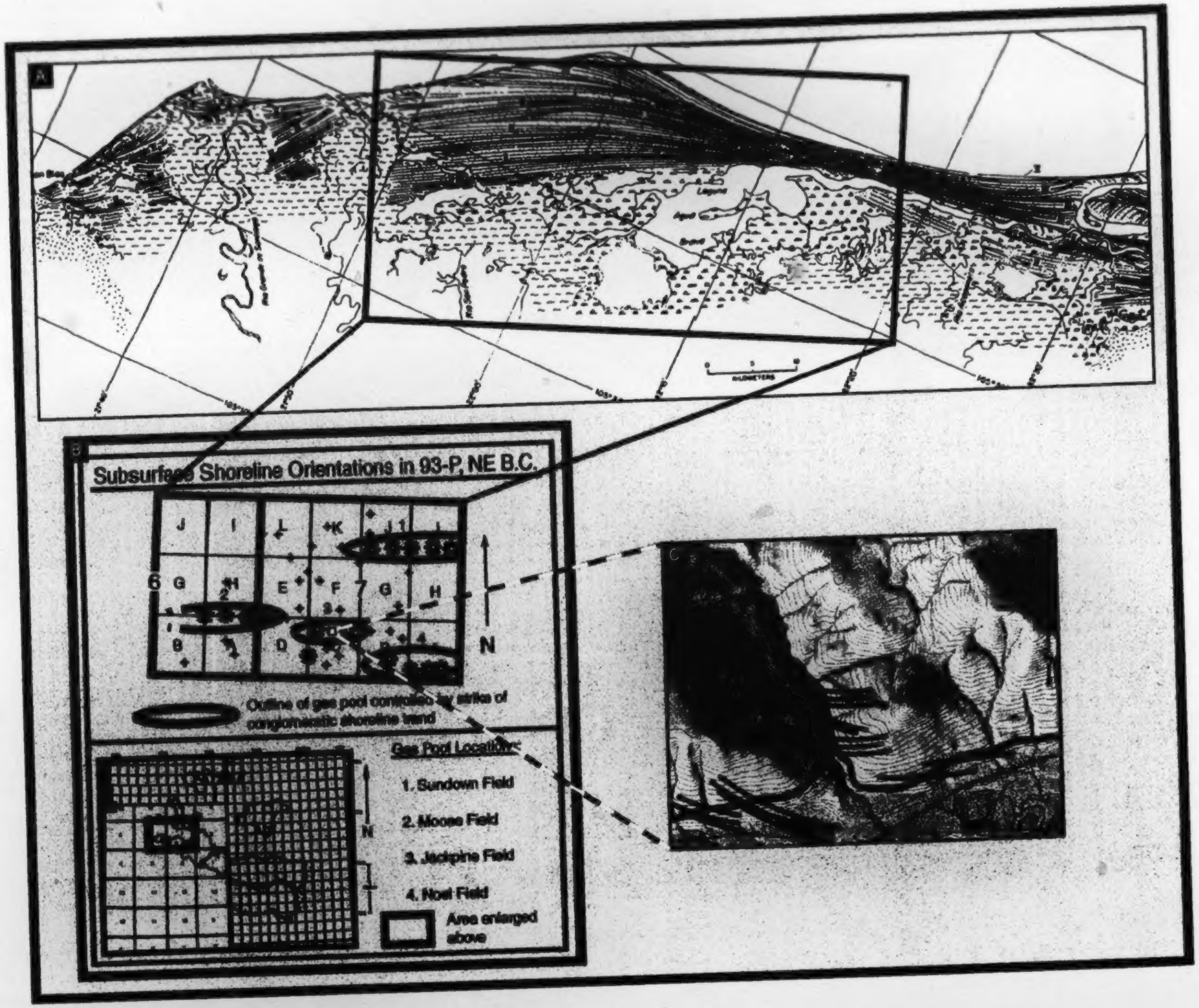
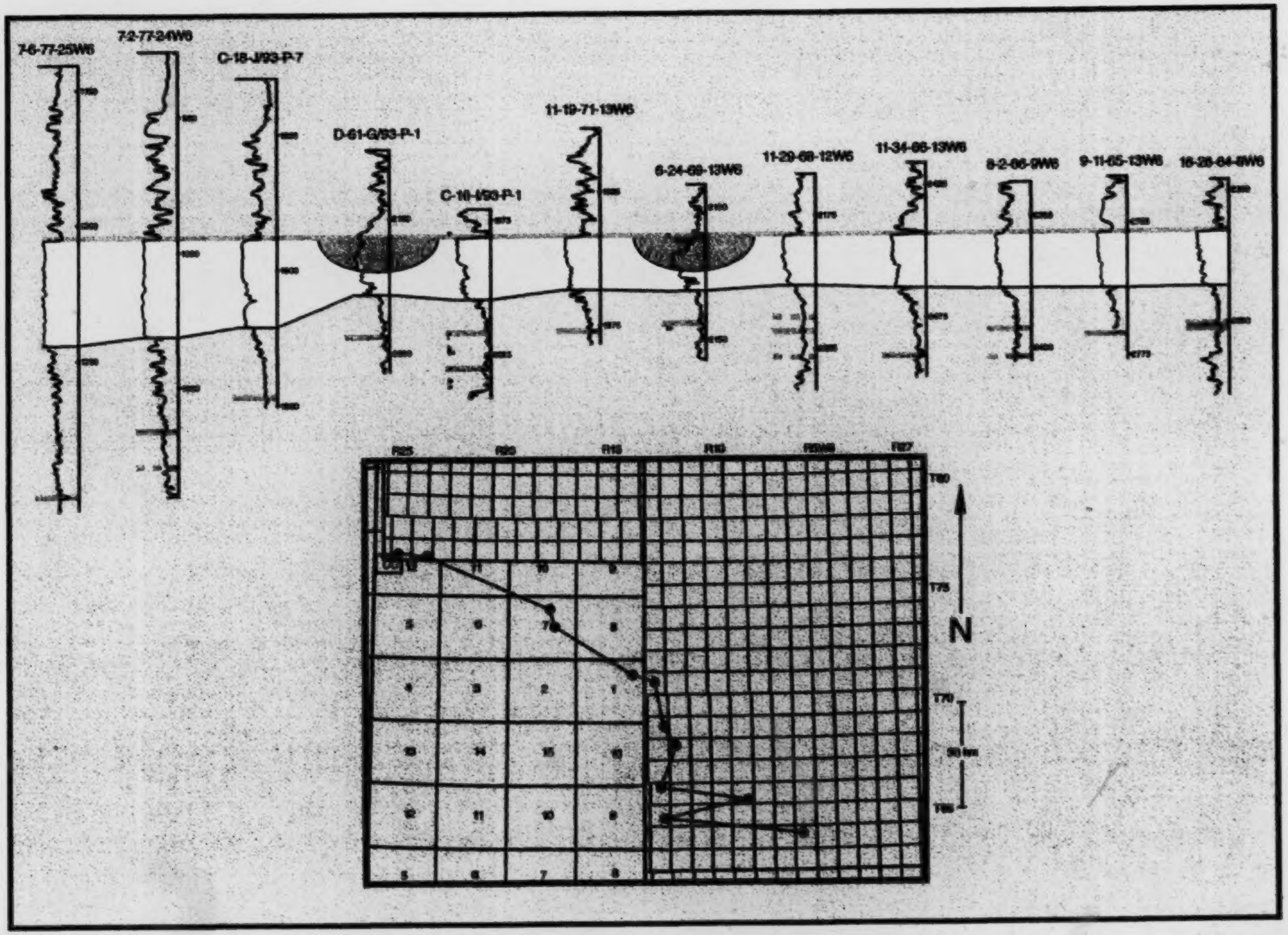

A
B
Subsurface Shoreline Orientations in 93-P, NE B.C.
J
I
L
K
J 1
G
H
E
F
G
H
6
7
2
3
4
1
B
D
N
Outline of gas pool controlled by strike of conglomeratic shoreline trend
Gas Pool Locations:
1. Sundown Field
2. Moose Field
3. Jackpine Field
4. Noel Field
N
Area enlarged above
C

Figure 3.9 – Regional gamma ray log cross section showing south, and east, thinning of Cadotte sandstone and conglomerate. The northwestward thickening of the Cadotte is attributed to increased accommodation in deeper portions of the Western Canadian Sedimentary Basin (and closer proximity to the Dawson Creek Graben Complex – tectonic control). Other possible controlling factors influencing the increased sedimentary thickness are sediment supply (larger supply of sand to pebble sized material) and, less conclusively, either a possible aggradational component to normal Cadotte shoreline progradation or the presence of a conglomeratic parasequence stacked directly above a sandy one. Orange lines on the gamma logs define the presence of a resistivity marker in the Harmon (dashed lines represent markers with a lower degree of confidence). Orange half circles (outlined in red) represent the presence of Cadotte channels.


7-6-77-25W6
7-2-77-24W6
C-18-J/93-P-7
D-61-G/93-P-1
C-16-I/93-P-1
11-19-71-13W6
6-24-69-13W6
11-29-68-12W6
11-34-66-13W6
8-2-66-9W6
9-11-65-13W6
16-26-64-8W6
R25
R20
R15
R10
R5W6
R27
T80
T75
T70
T65
50 km
N

CHAPTER 4 – BRIEF THESIS SUMMARY AND CONCLUDING REMARKS

4.1 Thesis Summary

The focus of this project was to provide detailed information regarding the deposition and progradation of outcropping Cadotte Member sedimentary rocks. Establishing basic study criteria (methodology, study area location, etc.), and placing the outcrop locations within a greater, regional setting was the primary goal of Chapter 1. This opening chapter focused on large-scale processes, distributions, and overall behavior, all in an attempt to give the reader a sense of what Western Canada was like circa 100 Ma ago (during which the Cadotte sediments would have been deposited and reworked).

Establishing the regional paleogeographic distribution of the unit provides the reader with information regarding where preserved Cadotte may be located today and what the Western Canadian Sea was like during the upper middle Albian, when the unit was originally emplaced. Discussion of storm systems and their possible tracks and controls helped set the stage for forthcoming conclusions directly related to the development of the depositional model.

Outlining major structural features and influences provided important information regarding Cadotte age basin configuration. It allowed the reader to visualize such things as "where is the deepest portion of the basin" and "is there supporting evidence for why Cadotte coastlines seem to overwhelmingly be oriented east west". Finally, the chapter closed with a discussion on the regional, as well as spatial-temporal, behavior of the unit. This discussion was by no means intended to be a definitive and conclusive solution to the question of systems tract allocation and possible cyclicity. Instead, its primary goal was simple: make the reader aware that this is an inconclusive issue and provide enough background information to allow them to draw some of their own conclusions throughout the course of the thesis.

Chapter 2 incorporated observations from both the Dokie Ridge and Commotion Creek localities into a highly defined facies succession. Individual Cadotte facies were laid out and interpreted while both the under, and overlying Facies Associations were described and discussed in less detail. Although long winded, description of the Cadotte facies succession was the single most important input required for the development of the depositional model (broken down in Chapter 3).

The principle goal of the 3rd chapter of the thesis, as mentioned above, was to establish and delineate a depositional model. However this was not the only goal of the chapter. Discussion regarding the 3-dimensional behavior of the Commotion Creek coastline, as well as comments regarding sediment source and regional behavior, were also undertaken in the hope of providing a more complete description of the overall behavior, and establishment, of the shoreline complex. In essence, Chapter 3 attempted to build and elaborate on many of the concepts or ideas laid out in earlier chapters.

4.2 Conclusions

Although there was much speculation throughout the course of this thesis some important conclusions can still be drawn. These conclusions will vary in their usefulness to hydrocarbon exploration as different study results address a variety of potential issues a petroleum geologist might face when working with this unit. Key conclusions are listed below:

1. The Cadotte is a coarse-grained coastal sedimentary package characterized by two dominant lithologies; very fine-to-fine grained quartz sandstones and very coarse chert sandstone/granule to small pebble conglomerates.
2. Lithology is an important reservoir-defining characteristic due to the influence of diagenesis (silica cementation). The quartz-dominated sandstones develop prolific quartz overgrowths. These overgrowths effectively diminish porosity and permeability. Chert lithologies tend to preserve a higher degree of both porosity and permeability, as when chert is cemented by quartz the cement takes the form

of quartz druse. The druse, coupled with the larger grain sizes of chert clasts helps preserve porosity and maintain open pore throats.

3. The highest degree of reservoir quality Cadotte sediment is that which has preserved the highest degree of unimodality (abundance of equant grain sizes). This characteristic has a tendency to be developed in gravel subjected to high degrees of winnowing and mobilization. Foreshore sediments generally exhibit this characteristic and therefore represent what could be thought of as the principle flow unit in potential Cadotte sequences/reservoirs.
4. In the Commotion Creek area, the Cadotte coastal succession was a high energy, storm dominated shoreface to strandplain system. This strandplain is thought to have developed in a setting proximal to a sediment point source (delta). High volumes of sediment (evident by the thickness of Cadotte facies) and the general nature of many of the shoreface, and associated subenvironments to be much coarser than sandier equivalents supports this line of thinking. Specifically the absence of any preserved record of suspension sedimentation in the offshore transition suggests that this succession is somewhat different than other classic examples of Cretaceous chert rich conglomeratic shoreline successions (ie. Falhers, Cardium).
5. Storm energy has an important control on coastal processes and shoreface morphology. The arrival of storm waves at the shoreface erodes and flattens the dominant fairweather shoreface profile. This flattening is accomplished by a change in the morphodynamic state of the shoreface from a more reflective to a more dissipative system. This dissipative system transports sediment further down the shoreface profile in an ephemeral rip channel-bar system that is itself destroyed upon a return to fairweather conditions, and therefore a more reflective character.
6. Seasonal climatic fluctuations are thought to be the most important control on whether the storm, or the fairweather, profile remains dominant (preserved).
7. The mappability and subtle variation in shoreface orientation in the Commotion Creek region suggests that the individual shoreface wedges present compose a

larger strandplain setting (which itself may be part of a larger delta system thought to be nearby).

8. High frequency variations in shoreface orientation will introduce complexity in any attempts to model flow behaviors within Cadotte reservoirs.
9. The high depositional permeability of the coarse-grained chert conglomerates encourages the development of a steeper shoreface profile than similar sand dominated systems. For this reason the coarsest sediment is effectively trapped close to the shoreline and therefore associated facies have a relatively narrow width with respect to basinward extent. This is important in that it suggests that if the exploration geologist sees evidence of coarse material in lower facies of a generally sand dominated succession, they may not have to explore much further landward of this showing to find the larger accumulation from which it was derived (possibly as little as a couple of hundred meters).
10. Sequence stratigraphic analysis of the Commotion Creek Cadotte is difficult given the coarse grained and high-energy nature of system (which limits the utility of biostratigraphy to delineate major temporal breaks). The proximity of the Commotion Creek shoreface-strandplain system to both the paleo-Fold and Thrust Belt coupled with the presence of the Dawson Creek Graben complex indicates that whatever sequence stratigraphic model is applied, its cyclicity and relative sea level fluctuations are control dominantly by tectonics.
11. Abundant proximal tectonic elements contribute to create a high accommodation setting into which the Commotion Creek Cadotte sediment was discharged.

These are but a few of the important conclusions derived from this study. The Cadotte is a dynamic and complex system that can easily cause a geologist a great deal of frustration. In closing, it should be stated that it was the author's experience that at the end of the day, no matter how many facies models exist, the most valuable and telling approach to analyzing the unit is to listen to what the rocks are telling you with respect to processes. With increased understanding of the dominant depositional processes the geologist is free to better, and more accurately, describe and model the unit (of course no matter how comprehensive the process summary, this will still not prevent every geologist from having a different opinion).

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APPENDIX A – SUMMARY OF DRILL PROGRAM

The drill coring component of this study was carried out by Anderson Water Wells (of Fort St. John British Columbia) from March 5 to 8th, 2002. The coring took place along the west side of the Walton Creek Forest Service Road (owned and operated by West Frasier), and required that the author obtain the proper permit from the B.C. Government Ministry of Energy and Mines. Weather during the week of the program consistenly approached -30°C during morning hours and may have reached as high as –15°C during the mid afternoon. As well, two nights before the initiation of the drill program, Chetwynd and the surrounding area experienced a blizzard which buried, and effectively sealed off road access to the drill location under 2-3 feet of fresh snow. The access road had to be plowed, and a 550 CAT was hired in the town of Chetwynd to come out and provide an access route to the drill site.

The total depth of the hole was 30.28 m consisting of 5.18 m of over burden, 5.78 m of interbedded sandstones and shales of the basal Walton Creek Member, 17.11 m of upper Cadotte Member chert pebble conglomerates and 2.21 m of lower Cadotte Member sandstones. The drilling was conducted using a 1978 Ingersroll Rand TH 60 top head rotary air drill (Figure A.1 C). Surface casing was set by using a casing hammer to drive the casing through the 5.18 m of surficial glacial till down to the top of the rock unit of interest. Coring was carried out using a core barrel (with internal split tube) equipped with a Christenson 9 cutter (and later a 12 cutter) diamond enhanced drill bit. During the course of the drilling , 3 new and 1 realigned drill bits were used, as the extremely hard and coarse-grained nature of the conglomerates continually abraded drill bit teeth to the point of being ineffective (Figure A.1 A and B). The first core recovered was 5.78 m of interbedded Walton Creek sandstones and shales. Drill rates through this interval were on the order of 2-3 m/hour. Shale interbeds were often fractured and rubbly, while the more compotent sandstones allowed for higher quality recovery (Figure A.2 A). Conglomerates of the underlying Cadotte Member posed the greatest problem for coring. 17.11 m of conglomerate was recovered, but 3 diamond enhanced dill-coring bits were worn down in the process, as the extremely hard nature of the rock prevented drill rates of any faster than 0.5 m/hour. The recovered conglomerate was pristine (except where coring encountered a natural fracture) and often came out of the core split tube as 1 long continuous piece (Figure A.2 B).

Financing and budgeting of the coring program consisted of two phases. A preliminary estimate of $25,300.15 was submitted to the author by Anderson Water Wells for the use of one core bit to drill and core to an anticipated depth of 40 m. However, the author's budget was $12,000.00 and so, Anderson Water Wells graciously donated time and a portion of the cost to allow the core program to continue. The preliminary program, as agreed upon by the author and Anderson Water Wells did not consider that more than one bit might be necessary to penetrate and core a maximum of 17.11 m of conglomerate, however after 10 m of conglomerate was recovered, it became evident that the bit was worn to the point of being ineffective and the preliminary program was therefore terminated.

A second program was immediately developed and emplaced to take advantage of the rig already being on location, with a principle goal of passing through the base of the conglomeratic section and ending somewhere within the underlying quartzose sandstones (the location of which was directly dependant on the endurance of the core bit). The costs associated with this program were estimated at $11,000.00, which included the use of a second coring bit and 1 additional day of rig time (with associated rig costs). Financing for continuation of the Drilling (phase 2) entailed a $5,000.00 contribution graciously provided by both BP Canada and Devon Petroleum, and a $1,000.00 contribution by ENSERC (awarded to Dr. S.G. Pemberton). This program commenced on the afternoon of March 7 at approximately 2:00 pm. By 6:30 pm that same day, after only 3 m of conglomerate core had been recovered, it was revealed that yet another bit had worn its teeth flat on the resistant conglomerate. At this point the driller (Simon Wolford) graciously volunteered, on behalf of Anderson Water Wells, to realign the teeth of the worn bit, and if necessary, provide a new Christenson 12 cutter coring bit, to allow for continuation and completion of the coring program (at Anderson Water Wells expense). The bit with the realigned teeth wore flat after another meter and a half of coring, and thus, was removed from the end of the drill string to be replaced with the new

Christenson 12 cutter core bit. Finally, at 5:00 pm on March 8th, 2002, the core program was terminated 2.21 m into the underlying quartzose sandstone, at a total depth of 29.48 m. In short, this program was extremely unpredictable and could not have been completed without the generous contributions of both finances and time provided by Anderson Water Wells, BP Canada and Devon Canada, all three are thanked for their help in aloowing this project to be carried out.

A summary breakdown of costs associated with this core program is provided in Table A.1.

Initial Project Cost Breakdown	Cost ($)
Initial Retail Cost Estimate	25,300.15
Initial Project Budget	12,000.00
AWW* Contributions	13,300.15
Secondary Cost Breakdown For Continued Coring	**Cost ($)**
Retail Estimate of Costs (From AWW)	11,000.00
Contribution From BP Canada	5,000.00
Contribution From Devon Canada	5,000.00
Contribution From S.G. Pemberton	1,000.00
Total Retail Cost Of Coring (Without Discounts)	36,300.15
Total Cost Of Coring (Including Discounts)	23,000.00

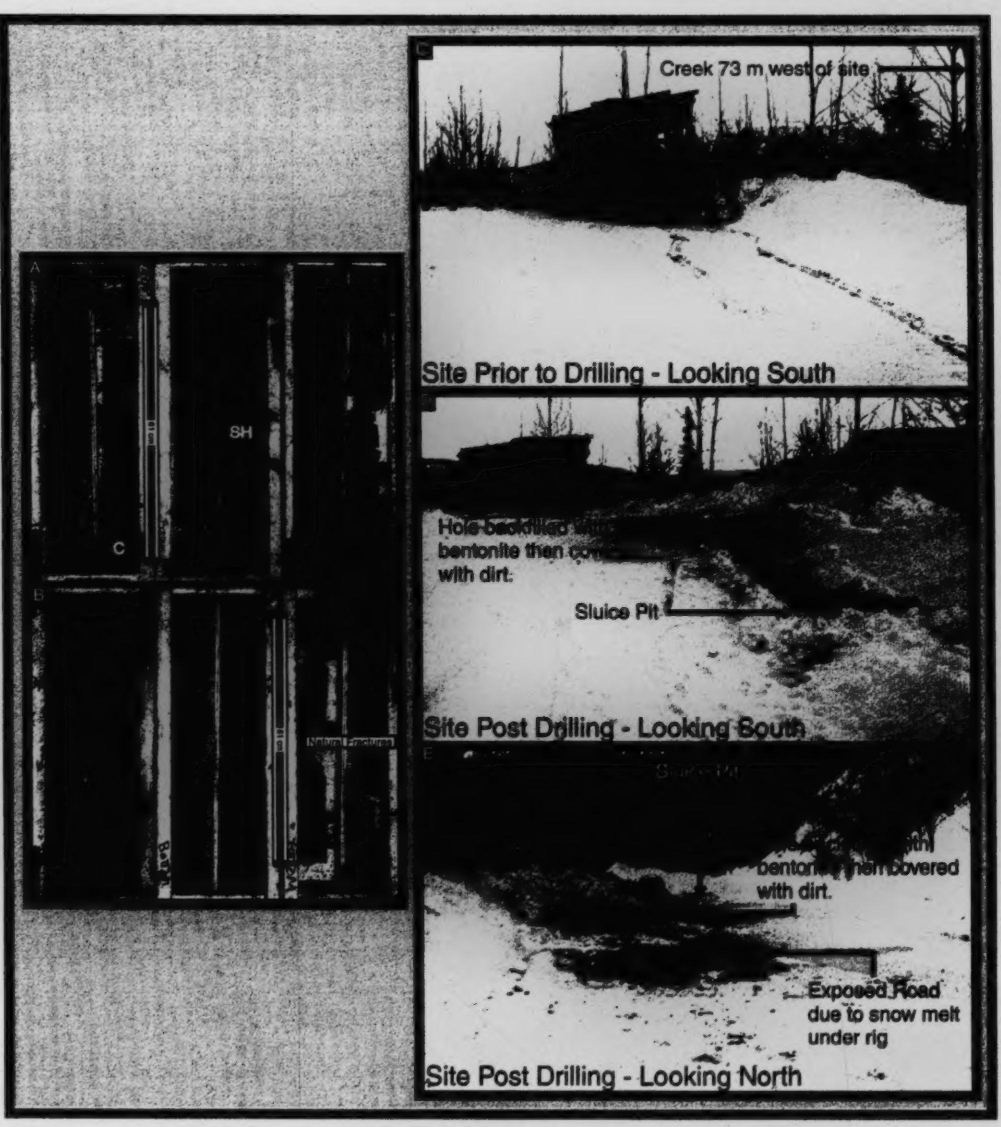
Table A.1 Cost breakdown associated with coring program
(*AWW – Anderson Water Wells)

Upon completion of the coring, the hole was backfilled with bentonite chips and covered with mud. Since the coring was completed using water, the environmental impact on the surrounding area was minimal, and the only government restriction was the establishment of a sluice pit, in which this coring fluid could be collected (Figure A.2 C, D and E).

Figure A.1 Before (A) and after (B) photos of the coring bit used to core the Commotion Creek Cadotte. C) Rig used by Anderson Water Wells in the coring process.

A
B
C

Figure A.2. Photos A and B show samples of the quality of recovery. A) Portion of the Walton Creek showing the friable nature of both coal (C) and shale (SH), while the sandstone (SS) tends to be more resistant (as does the conglomerate in B). Photos C, D and E show before and after images of the coring site.


A
61 cm
SH
C
B
61 cm
Natural Fractures
C
Creek 73 m west of site
Site Prior to Drilling - Looking South
D
Hole backfilled with bentonite then covered with dirt.
Sluice Pit
Site Post Drilling - Looking South
E
Sluice Pit
with bentonite then covered with dirt.
Exposed Road due to snow melt under rig
Site Post Drilling - Looking North